CHAPTER 3. TECHNOLOGY ASSESSMENT

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High-intensity discharge (HID) lamps produce light by generating an electrical discharge between electrodes contained within an arc tube. By definition, HID lamps include mercury vapor (MV), high-pressure sodium (HPS), and metal halide (MH) lamps. HID lamps range from 20 to 2000 watts (W). The lamps are often subdivided by power into low (less than 150), medium (from 150 to 500), and high (greater than 500) wattages. Because the electrical discharge exhibits a negative resistance, ballasts regulate this electrical discharge and prevent it from drawing excessive current that would lead to premature lamp failure. Therefore, HID lamps always operate with a ballast, which is typically external to the lamp and located within the luminaire. There are limited exceptions to this configuration, specifically self-ballasted (integral ballast) MV lamps and the MH parabolic aluminized reflector (PAR) lamps.

The following discussion examines and summarizes current specifications, standards, and guidelines governing the classification, testing, and evaluation of HID lamps. Because this analysis considers lamps only, issues concerning the effects of ballasts on HID lamp performance are outside the scope of this analysis. However, the availability, capability, and functional relationship of ballasts and lamps are important for understanding the technology and its market. Therefore, as appropriate, ballasts and their characteristics are addressed in this section.

3.1 SPECIFICATIONS, TEST STANDARDS, AND PROCEDURES

The U.S. Department of Energy (DOE) reviewed available evaluations of the electrical and photometric properties of HID lamps and ballasts. Table 3.1.1 presents a list of industry standards publications pertaining to HID lighting systems.

Table 3.1.1 Documents Pertaining to High-Intensity Discharge Lamps

Source	#	Year	Title
ANSI*	C78.1381	1998	*American National Standard for Electric Lamps—70 W, M85 Double-Ended MH Lamps*
	C78.380	2007	*American National Standard for Electric Lamps-High-Intensity Discharge Lamps, Method of Designation*
	C78.380a	2004	*American National Standard for Electric Lamps-HID Lamps, Method of Designation (Amendment)*
	C78.389	2004 R2009	*American National Standard for Electric Lamps – High Intensity Discharge — Methods of Measuring Characteristics*
	C78.40	1992 R2003	*Specifications for Mercury Lamps*
	C78.40a	1998	*American National Standard for Specification for Mercury Lamps-Maximum Outline Drawing of Bulb BT56*
	C78.42	2007	*American National Standard for Electric Lamps-HPS Lamps*
	C78.43	2007	*American National Standards for Electric Lamps-Single-Ended MH Lamps*
	C78.44	2008	*American National Standards for Electric Lamps-Double-Ended MH Lamps*
	C78.45	2007	*American National Standard for Electric Lamps-Self-Ballasted Mercury Lamps*
	C78.LL 3	2003	*Procedures for HID Lamp Sample Preparation and the Toxicity Characteristics Leaching Procedure (TCLP)*
	C81.62	2007	*American National Standard for Electric Lampholders*

Table 3.1.1 (continued)

Source	#	Year	Title
ANSI* (contd.)	C82.4	2002	*American National Standard for Ballasts for HID and Low-Pressure Sodium (LPS) Lamps (Multiple-Supply Type)*
	C82.6	2005	*American National Standard for Lamp Ballasts – Ballasts for HID Lamps-Methods of Measurement*
	C82.9	1996	*American National Standard for HID and Low-Pressure Sodium (LPS) Lamps, Ballasts and Transformers—Definitions*
	C82.14	2006	*American National Standard for Lamp Ballasts-Low-Frequency Square Wave Electronic Ballasts-for MH Lamps*
IESNA**	LM-31-95	1995	*Photometric Testing of Roadway Luminaires Using Incandescent Filament and High Intensity Discharge Lamps*
	LM-35-02	2002	*Photometric Testing of Floodlights Using HID or Incandescent Filament Lamps*
	LM-46-04	2004	*IESNA Approved Method for Photometric Testing of Indoor Luminaires Using HID or Incandescent Filament Lamps*
	LM-47-01	2001	*IESNA Approved Method for Life-Testing of HID Lamps*
	LM-51-00	2000	*IESNA Approved Method for the Electrical and Photometric Measurements of High Intensity Discharge Lamps*
	LM-61-06	2006	*IESNA Approved Guide for Identifying Operating Factors Influencing Measured vs. Predicted Performance for Installed Outdoor HID Luminaires*
	LM-73-04	2004	*IESNA Guide for Photometric Testing of Entertainment Lighting Luminaires Using Incandescent Filament Lamps or High Intensity Discharge Lamps*
NEMA†	LE 5B	1998	*Procedure for Determining Luminaire Efficacy Ratings for HID Industrial Luminaires*
	LSD 14	2002	*Guidelines on the Application of Dimming to HID Lamps*
	LSD 24	2003	*Marking of Luminaire Codes on MH Lamps*
	LSD 25	2008	*Best Practices for MH Lighting Systems, Plus Questions and Answers about Lamp Ruptures in MH Lighting Systems*
	LSD 31	2005	*A Lighting Systems Division Information Bulletin: Changes to the 2005 NEC Will Impact Future MH Lamp Systems Options*
	LSD 35	2006	*ANSI Code Update to Include Letter "C" for Ceramic MH Lamps*
	LSD 37	2008	*Effects of EPAct 2005 on MV Lamp Ballasts and Lighting Systems: Frequently Asked Questions*
	LSD 54	2010	*The Strengths and Potentials of Metal Halide Lighting Systems*

* ANSI = American National Standards Institute.
** IESNA=Illuminating Engineering Society of North America.
† NEMA = National Electrical Manufacturers Association.
Sources: NEMA website (http://www.nema.org), 2010; IESNA website (http://www.iesna.org), 2010.

As the Secretariat for ANSI, NEMA publishes standards for lamps (C78), bulbs (C79), lamp bases and holders (C81), and ballasts (C82); standards for performing standardized tests to evaluate the energy efficiency of luminaires (LE); and general information documents (LSD) as part of its lighting-standards program.[1] Table 3.1.1 presents the ANSI standards specifically related to HID technology, excluding the more generally-applicable standards for bulbs (C79) and lamp bases and holders (C81).

ANSI also publishes a nomenclature for the designation of HID lamps in its C78 technical support documents. At a minimum, the designation code includes the class and electrical characteristics of the lamp. In addition, ANSI publishes a set of corresponding performance and physical characteristics specifications. The designations and specifications not only provide a system of identification, but also ensure a level of product commonality and interchangeability among manufacturers of HID lamps and ballasts.

IESNA is another organization promulgating standards for HID lamps and related technologies, including lighting measurement (LM) test procedure documents. IESNA LM-35-02, LM-46-04, and LM-73-04 focus on testing luminaires using HID technology (as well as other light sources). IESNA LM-41-01 and LM-51-00 focus on life and electrical/photometric measurements of HID lamps, respectively. These publications build on ANSI standards to include procedures for both electrical measurements and photometric measurements by defining testing conditions, lamp stabilization, and other critical aspects to ensure consistency in the testing of lamp performance. Publications by IESNA reflect the consensus of industry stakeholders, including NEMA members.

3.2 LAMP METRICS

Lamp characteristics and performance are evaluated on a number of factors, in addition to lumen output. The following is a review of different metrics applicable to HID lamps.

3.2.1 Lumens

The lumen (lm) is the basic unit of light. The IESNA defines luminous flux as the time rate of flow of radiant energy, evaluated in terms of a standardized visual response[2]:

$$\Phi = 683 \times \int_{380}^{780} \boldsymbol{SPD}\,(\boldsymbol{\lambda}) \times \boldsymbol{V}\,(\boldsymbol{\lambda}) \boldsymbol{d\lambda} \qquad \textbf{Eq. 3-1}$$

Where:

Φ = luminous flux (in lumens, lm).

The value of 683 lumens per watt (lm/W) is a constant for the photopic luminous efficacy function. The equation essentially is the integral of the light source's spectral content expressed as spectral power distribution (SPD) over the visible range of the electromagnetic spectrum weighted by the photopic luminous efficacy function. In practical terms, this equation expresses integrating the energy emitted by the light source across the visible light portion of the spectrum (380 to 780 nanometers [nm]) and multiplying by the visual efficacy function (a function weighting the different portions of the visible light spectrum by the different photoreceptors in the eye) times the constant 683 lm/W. The units cancel out to just lumens.

3.2.2 Mean Lumens/Lamp Lumen Depreciation/Lumen Maintenance

Lamp lumen depreciation (LLD) is also known as lumen maintenance. In use, a lamp loses light output over time. According to the IESNA, the LLD factor is "the fraction of the initial lumens produced at a specific time during the life of the lamp."[2] The LLD value is used in lighting calculations to account for the reduction in output over the operating life of the lamp. Often the mean (also known as design) lumens are used for LLD. Mean lumens are published in the manufacturers' catalogs and are measured at a certain point in time, typically a specific percentage of the lamp's rated lifetime.

The IESNA does not define when to measure mean lumens; however, 70 percent of average rated life is the recommended criterion for lamp replacement for both group and spot relamping programs.[2] This value is usually not used in design calculations because it is difficult to determine from manufacturers' data. Often, designers must build margins into their calculations and use the mean/design lumen value presented in the catalogs.

The basis for mean lumens can vary among manufacturers, as shown in DOE's survey of definitions from manufacturer catalogs:

> GE: "Mean Lumens – lamp light output at 40% of rated lamp life for (MH) lamps and 50% of rated life for mercury and HPS lamps."[3]
>
> OSRAM SYLVANIA: "Mean lumens are measured on ANSI reference circuits at rated wattage (HQI, LUMALUX Super and SO_X lamp ratings are based on input voltage) at 40% of average rated life except for those lamps with a "+" next to their life rating; these lamps are measured at 50% of average rated life. All measurements are based on ballast operation on systems with current crest factors of 1.8 or less. Higher current crest factors reduce values. In actual applications on constant wattage (CW) or constant-wattage autotransformer (CWA) ballasts, mean lumens may be higher than published ratings."[4]
>
> Philips: "Approximate lumen output at 40% of lamp rated average life."[5]
>
> USHIO: "Lumens, Mean: Average quantity of light output over the life of the lamp. High Pressure Sodium and incandescent lamps are measured for mean lumens at 50% of lamp life. Fluorescent and MH lamps are measured for mean lumens at 40% of rated lamp life."[6]
>
> Venture (a manufacturer of only MH lamps): "Mean Lumens: Light output at 40% of rated life."[7]

Chapter 2, Market Assessment, discusses both draft legislation focusing on outdoor lighting and requirements related to mean lumens that are already in effect in California. The absence of an agreed-upon definition for mean lumens complicates any discussion of standards compliance or recommended relamping cycles and hinders comparisons of similar products from different manufacturers.

3.2.3 Color Rendering Index

The IESNA defines color rendering index (CRI) as "a measure of the degree of color shift objects undergo when illuminated by the light source as compared with those same objects when illuminated by a reference source of comparable color temperature."[2] In CRI calculation, 14 samples are evaluated; however, the general CRI (Ra) is only an average of the first 8 samples. Samples R1–R8 are not highly saturated and are pastel colors. R9 is an oft-cited color value because it is a deeply saturated red. The accurate rendering of this color is often desired in retail applications. Light emitted at the "red end" of the visual spectrum (above 700 nm) adds little to total lumen output, but can add important color qualities to the lamp. Incandescent and halogen lamps have R9 values of 100. The R9 value for HID lamps can be negative and is often 0 because these sources do not emit significant light above 700 nm.

3.2.4 Correlated Color Temperature

The IESNA defines correlated color temperature (CCT) as "the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source." Color temperature is a not a performance metric but rather characterizes the color appearance of a light source: "Color temperature is a specification of chromaticity only. It does not represent the SPD of the light source."[2] Chromaticity (expressed as chromaticity coordinates, *e.g.*, x and y) is a representation of the light source color calculated with by the standard observer and spectroradiometric measurements.

3.2.5 Efficacy

Efficacy (luminous efficacy) is defined by the IESNA as quotient of the total emitted luminous flux and the total lamp power. Expressed mathematically:

$$\eta = \text{luminous flux (lm) / lamp power (W)} \qquad \textbf{Eq. 3-2}$$

Where:

η = luminous efficacy (in lumens per watt, lm/W).

A 2001 paper by Nelson et al., "An Efficacy Analysis of HID Lamps," examined the components of efficacy of HID lamps.[8] The paper was not entirely based on new research, but also on long-standing lighting science. The paper focused on aspects of efficacy irrespective of chromaticity and color rendering. The paper only examined lamp efficacy and excluded lighting system (*i.e.*, ballasts and fixtures). The paper converted the mathematical efficacy function into the three components, rewritten as:

$$\eta = \eta_{vis} \times \eta_{max\ spectral} \times \eta_{spectral} \times 683 \text{ lm/W} \qquad \textbf{Eq. 3-3}$$

Where:

η_{vis} = visual efficiency,
$\eta_{max\ spectral}$ = maximum spectral efficiency,
$\eta_{spectral}$ = spectral efficiency, and
lm/W = lumens per watt.

The value of 683 lm/W is both a constant and the absolute photopic luminous efficacy value. Therefore, as the different η values approach 1.0, the closer the efficacy is to 683 lm/W.

3.2.5.1 Visual Efficiency

The visual efficiency of a lamp is the quotient of the power radiated in the visible spectrum (380 to 780 nm) and the total lamp power. Table 3.2.1 is from Nelson et al.[8]

Table 3.2.1. Visual Efficiencies and Efficacies of Various Sources

Lamp Type	Pla* *W*	η_{vis}	η *lm/W*
High-Pressure Sodium	150	0.22	90
	400	0.31	124
	1000	0.33	135
White High-Pressure Sodium	100	0.20	51
Mercury Vapor	400	0.15	55
Quartz Metal Halide–NaSc Pulse Start	400	0.35	110
Quartz Metal Halide–NaTl In	400	0.24	80
Ceramic Metal Halide–3000 K	100	0.35	98
Ceramic Metal Halide–4000 K	100	0.38	95

*Pla = Power of the lamp.

The data in Table 3.2.1 reflect visual efficiencies ranging from 0.15 to 0.38. Newly developed (post-1990) HID lamps (pulse-start ceramic and quartz MH) have visual efficiencies above 0.35. As lamp power increases so does visual efficiency, as shown in the HPS data (150 W/0.22, 400 W/0.31, 1000 W/0.33). Although related, changes in visual efficiency do not directly correlate to changes in efficacy. The white HPS lamp has a slightly lower efficacy than the mercury vapor, yet the HPS lamp has more visual efficiency, with values being virtually the same for the 150 W HPS (0.22) and the white HPS (0.20). The efficacy of the 150 W lamp is almost twice that of the 100 W white HPS lamp.

Table 3.2.2 is excerpted from the *IESNA Lighting Handbook*, table 7-49.[2] Each of the HID lamps produces more infrared radiation (IR) than visible light. This distribution of energy directly affects the visual efficiency value of the lamp. If the HID lamps produced more energy in the visual light region of the electromagnetic spectrum, the visual efficiency values would be greater.

Table 3.2.2. Sample Energy Output for High-Intensity Discharge Lamps

Type of Energy	400 W %		
	MV	**MH**	**HPS**
Visible Light	14.6	20.6	25.5
Infrared	46.6	31.9	37.2
Ultraviolet	1.9	2.7	0.2
Conduction-Convection	27.0	31.1	22.2
Ballast	10.1	13.7	14.9

Maximum Spectral Efficiency. Nelson et al. (2001) defined the maximum spectral efficiency a factor expressing the effect of the eye sensitivity curve for a given chromaticity. A given lamp's location in color space factors into efficacy and that is the role of the maximum spectral efficiency.

Nelson et al. provided the chromaticities maximum spectral efficiencies for the lamps that it provided the visual efficiency data for, which are shown in Table 3.2.3. The paper found (and supported by the data republished) that the maximum spectral efficiency varied from 0.70 to 0.76 for HID lamps.[8]

Table 3.2.3. Chromaticities and Maximum Spectral Efficiencies of Various Sources

Lamp Type	Pla *W*	x	y	CCT	$\eta_{max\ spectral}$
High-Pressure Sodium	150	0.521	0.423	2100	0.75
	400	0.521	0.413	2040	0.72
	1000	0.522	0.413	2040	0.72
White High-Pressure Sodium	100	0.461	0.405	2640	0.75
Mercury Vapor	400	0.331	0.395	5680	0.73
Quartz Metal Halide–NaSc Pulse Start	400	0.374	0.394	4280	0.75
Quartz Metal Halide–NaTl In	400	0.390	0.398	3890	0.76
Ceramic Metal Halide–3000 K	400	0.368	0.368	4300	0.71
Ceramic Metal Halide–4000 K	100	0.433	0.388	2950	0.73
High-Pressure Sodium	100	0.372	0.366	4150	0.70

Spectral Efficiency. The spectral efficiency is a measure of how well a given spectrum is distributed relative to the optimally efficient two-line spectrum for that chromaticity. There is a negative correlation with spectral efficiency. As spectral efficiency increases, CRI decreases. This is demonstrated in the high spectral values for HPS and MV (0.82 and 0.77, respectively) and the very low CRI values of 11 (HPS) and 17 (MV). In contrast, the high CRI values of 93 and 89 from the HPS had lower spectral efficiency values (0.53 and 0.56, respectively; Table 3.2.4).

Table 3.2.4. Color Rendering Indexes and Spectral Efficiencies of High-Intensity Discharge Sources

Lamp Type	Pla *W*	CRI	$\eta_{max\ spectral}$
High-Pressure Sodium	150	11	0.82
	400	21	0.80
	1000	17	0.82
White High-Pressure Sodium	100	84	0.50
Mercury Vapor	400	17	0.77
Quartz Metal Halide–NaSc Pulse Start	400	36	0.70
Quartz Metal Halide–NaTl In	400	65	0.62
Ceramic Metal Halide–3000 K	400	62	0.67
Ceramic Metal Halide–4000 K	100	89	0.56
High-Pressure Sodium	100	93	0.53

Nelson et al. (2001) found that this negative relationship did exist and derived a function expressing the relationship of CRI and spectral efficiency for HID and LPS lamps. The function was a straight line with an R^2 value of 0.95 and is: $\eta_{spectral} = 0.8461 - (0.0034 \times \mathrm{CRI})$.[8]

Potential Efficacy Limits. Nelson et al. hypothesized the possible efficacy limits for conventional HID lamps on the blackbody locus (BBL), based on their assumptions in the 2001 paper.[8] The authors assumed a visual efficiency value of 0.40. Based on the lamps they surveyed, a value 0.38 was the highest for HID lamps. In the discussion section of their paper, this value was questioned. The authors defended their choice in that it represented a likely value for long-life, commercially available lamps with electrodes. The maximum spectral efficiency values were provided for the different chromaticities. Finally, a CRI of 80 was assumed, and using the function provided, the spectral efficiency values were derived. The authors chose a CRI 80 because end users will be more concerned with color quality in the future. A CRI of 80 seems reasonable when reviewing other DOE lamp rules. Table 3.2.5 is a review of the probable efficacy limits for HID lamps that lie on the BBL and have a CRI of 80. In review, the efficacy ranges from 100 to 120 lm/W, depending on the lamp chromaticity.

Table 3.2.5. Probable Efficacy Limits by Color Correlated Temperature for Conventional High-Intensity Discharge Lamps

CCT	η_{vis}	$\eta_{max\ spectral}$	$\eta_{spectral}$	η *lm/W*
2000	0.40	0.722	0.574	113
2800	0.40	0.766	0.574	120
3000	0.40	0.763	0.574	120
4000	0.40	0.722	0.574	113
5000	0.40	0.676	0.574	106
6000	0.40	0.636	0.574	100

3.2.5.2 Moving Beyond the Limits

Nelson et al. hypothesized that improving the power balance could increase the visual efficiency. Of the three values in the efficacy function, this value was below 0.4. Also, as stated in Table 3.2.2, only 15 to 26 percent of the energy being used by HID lamps is in the visual light portion of the spectrum. Nelson et al. hypothesized that the "a" source, such as the sulfur lamp with a visual efficiency of 0.55 at 3000 kelvin (K) on the BBL and a CRI of 80, could have an efficacy of 170 lm/W.[8] It should be stated that the sulfur lamp is no longer in production, but one reason that the lamp has a higher visual efficiency value is that it does not have electrodes.

Nelson et al. hypothesized that spectral optimization would increase the spectral efficiency. As shown in Table 3.2.5, the spectral efficiency values are limited to 0.574 due to the CRI of 80. If the spectrum was more optimized and the CRI held constant, the spectral efficiency values could be 0.80, resulting in a 170 lm/W lamp. Nelson et al. point out that the measures could be used in conjunction, yielding in a possible 230 lm/W lamp. Finally, the authors note that "even after more than 50 years of HID lamp development, the task of achieving a lamp with a high luminous efficacy (say, greater than 150 lm/w [LPW]), high CRI and a chromaticity near the black body line will not be an easy one."[8]

3.2.6 Lamp Life

The rated lamp life is defined when 50 percent of a sample group of lamps have failed. Rated lamp life is expressed in hours and varies with the method by which the ballast starts and operates the lamp.

3.3 MERCURY VAPOR LAMPS

Introduced in the 1930s, mercury vapor was the first commercialized HID light source and remains fundamentally unchanged. Mercury vapor and fluorescent (FL) lamps are both MV discharge lamps, but FL lamps operate at low pressure and MV lamps operate at high pressure.

One development in the movement toward efficient lighting was the invention of a self-ballasted MV lamp. This lamp originated as a longer-life substitute for the A-shaped general service incandescent lamp. By using a length of tungsten filament within the lamp structure to regulate current, these lamps function without ballasts. Although more efficient than incandescent lamps, these lamps are less efficacious than MV lamps with ballasts due to the resistive loss at the tungsten filament.

Because of their low CRI (15 is typical), MV lamps are used primarily in spaces that are not frequently occupied by people. A phosphor coating is added to clear MV bulbs to obtain better CRI, but the improvement is marginal. Outdoor security, street, and landscape lighting are some of the applications for MV lamps, but higher performing MH and HPS lamps are replacing these. MV systems continue to maintain market share in some niche applications (*e.g.*, the "security" or "barn" light—an arm-mounted luminaire typically used in residential applications) where long life and low initial cost are important. However, even in niche applications, MV is losing its advantage as other HID sources offer improved lifetime and initial cost. MV lamps are available in wattages from 50 to 1000.

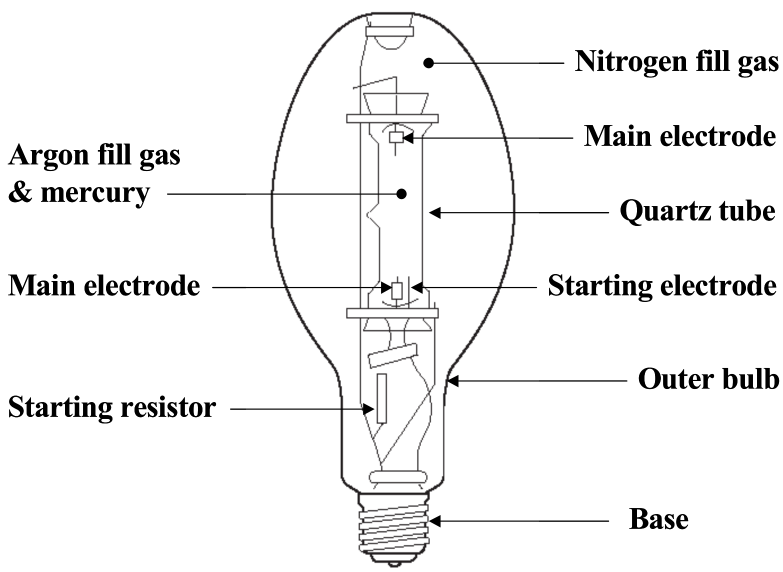
Mercury vapor lamps have applications aside from general illumination, including quality inspection, processing, scientific uses, reprographic (copy/duplication), fluorescent microscopy, and curing. The specific spectrum of MV lamps is beneficial to these applications. The self-ballasted MV lamp has special niche because of its unique capability to directly replace high-wattage incandescent lamps in standard mogul bases. Self-ballasted MV lamps are available in wattages between 100 and 400. Typical applications have included outdoor security lighting, area lighting, and some warehouse use. Although MV lamps offer modest energy savings over incandescent lamps, their more significant advantage over incandescent and other technologies is lamp lifetime, resulting in longer intervals between relamping. In recent years, the self-ballasted MV lamp has lost market share to integrally ballasted compact fluorescent lamps, integrally ballasted MH lamps, and even light-emitting diode replacement lamps.

3.3.1 Lamp Construction

In an MV lamp arc tube, an electric-current arc passes from the starting electrode to the main electrode. The initial arc strikes through the ionization of argon gas. Once the arc is established, its heat vaporizes the liquid mercury in the arc tube. The amount of mercury in the lamp essentially determines the final operating pressure, which is 200 to 400 kilopascals (kPa) (29 to 58 pounds per square inch) in the majority of lamps.[2] The arc tube construction is fused silica (quartz) that can operate at up to 1000 degrees Celsius (°C).

An outer glass envelope (bulb) protects the arc tube and internal electrical connections from the environment. The bulb is usually in the shape of an ellipse and made of hard (borosilicate) glass, which absorbs most of the ultraviolet (UV) energy radiated by the discharge while allowing light to pass through. For lamps where UV emission is desired (*e.g.*, germicidal lamps), the bulb is made of other materials that allow transmission of UV energy.[2] In coated MV lamps, the bulb is coated internally with a diffusing material to reduce source brightness of the lamp. This diffusing coating is usually a color-correcting phosphor that uses UV energy radiated by the arc tube to improve the lamp's overall color-rendering properties, as in a fluorescent lamp. MV lamps are also available in a reflector lamp format.

There are wires within the outer bulb that are suitable for high temperatures to conduct electricity to the arc tube and structural components to support the arc tube. The atmosphere in the outer bulb is usually a low-pressure gas (usually nitrogen) or, in rare cases, a vacuum.[2] If the outer bulb breaks and the arc tube continue to operate, the lamp emits a significant amount of UV energy. Self-extinguishing lamps, designed to shut off the lamp should the outer bulb break, usually contain a tungsten filament in place of a portion of nickel wire that oxidizes quickly, opening the circuit. This separation renders the lamp inoperable. Figure 3.3.1 shows essential construction details typical of lamps with quartz inner-arc tubes within an outer envelope.[2]



Source: GE Lighting, *High-Intensity Discharge Lamps Catalog*, 2003. Reproduced with permission.[9]

Figure 3.3.1. Mercury Vapor Lamp Construction

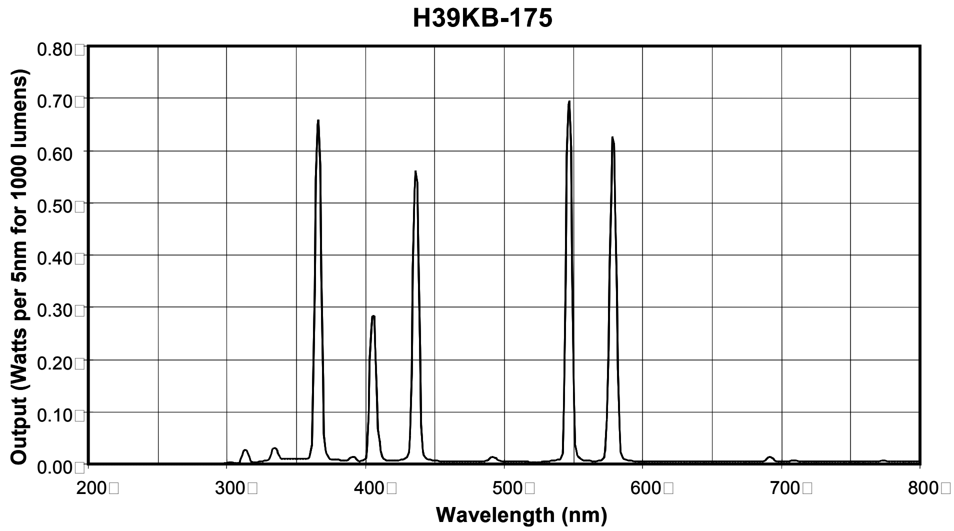
3.3.2 Lamp Performance

The pressure at which MV lamps operate has a significant effect on their characteristic SPD. As pressure increases, the emitted radiation shifts toward longer wavelengths (from UV to visible light) and the spectrum lines spread into wider bands. Within the visible region, the mercury spectrum consists of five principal lines (404.7, 435.8, 546.1, 577, and 579 nm), which result in greenish-blue light at efficacies of 30 to 65 lm/W, excluding ballast losses.[a, 2] While the light source itself appears greenish-blue white, a deficiency of long-wavelength radiation distorts the perceived color of objects illuminated by that light source. Blue, green, and yellow are emphasized; orange and red appear brownish. MV lamps also emit radiation outside the visible region in the form of UV in the range of approximately 250 to 365 nm. These wavelengths do

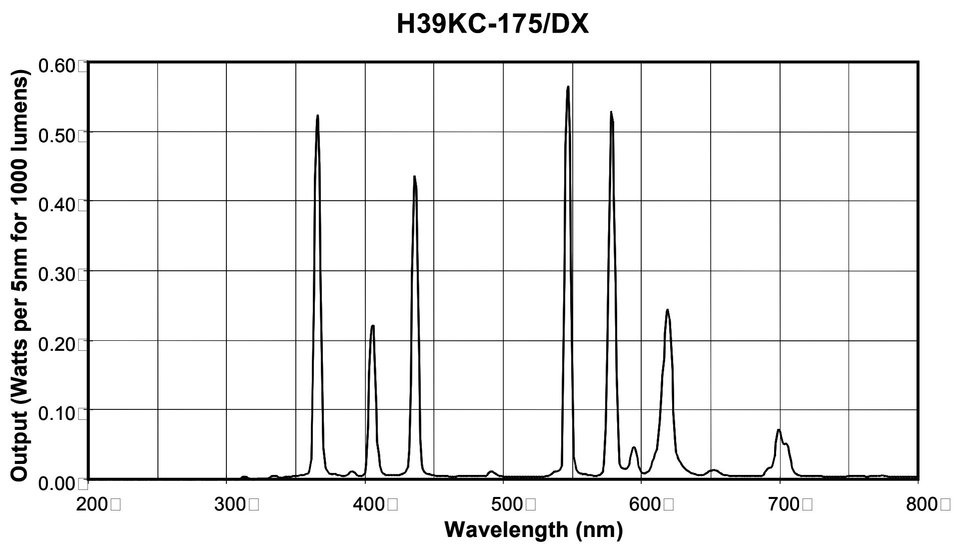
[a] Ballast loss – Power drawn by the ballast in addition to the rated lamp power used to operate the lamp.

not contribute to seeing, but are useful for non-illumination purposes (*e.g.*, reprographic or germicidal applications).

Clear MV lamps generally have a CRI value of approximately 15 and are not desirable for use where people will occupy the space. Phosphor-coated MV lamps convert some of the lamp's UV radiation to visible light, as occurs with a FL lamp. The most widely used lamps of this type (designated "DX") have a coating of vanadate phosphor that emits long-wavelength radiation (orange-red) where MV lamps are otherwise deficient, thus improving CRI.[2] This phosphor may also blend with other phosphors to produce a cooler or warmer CCT between 3200 and 7000 K. The phosphor coating can raise the CRI rating to 50. Figure 3.3.2 shows the SPDs of a clear lamp and coated lamp using these phosphors.



(a)



(b)

Source: OSRAM SYLVANIA, 2003. Reproduced with permission.[10]

Figure 3.3.2. Spectral Power Distribution of Mercury Vapor Lamps (a) Without Phosphors and (b) With Phosphors

Efficacies of self-ballasted MV lamps are slightly better than those of the incandescent lamps they replace. Typically, efficacies range between 15 to 25 lm/W. The spectrum consists of the line spectrum of mercury in addition to the blackbody radiation pattern from the incandescent component of the tungsten filament broadening the spectrum into long-wavelength range (red). Although the light in these wavelengths does not significantly increase total light output, it does increase the CRI of the source. The CCT ranges from 3300 to 4000 K, with a CRI of 50, depending on mercury pressure and phosphor coating used (if any).

The light output from MV lamps decreases over the operating life of the lamp. Typically, lumen output depreciates about 25 percent from initial output level at 50 percent of its rated life. The depreciation in light output is a result of the bulb becoming darker because the cathode material evaporates through use and is deposited on the wall of the arc tube bulb. Typical rated life is 24,000 hours, but it is common for the lamp to continue operating long after its rated life. One of the major failure points for discharge lamps is that the cathode material eventually evaporates and fails to strike an arc. MV lamps are notorious for never burning out, but simply diminishing in output over time because the evaporating cathode material has to diffuse through mercury vapor, a very heavy gas at high pressure, thereby slowing the evaporation process. The lamp power remains constant as light output declines, meaning that the efficacy of the light source steadily decreases over time.

To achieve the necessary high vapor pressures within the arc tube, MV lamps require a significant warm-up time of approximately 5 to 7 minutes. Re-strike times are about as long, requiring 5 to 7 minutes for the vapor pressure to reach the level where the arc can restart. Warm-up time for self-ballasted lamps is approximately 3 minutes, with a re-strike time of 5 minutes. Table 3.3.1 summarizes the performance of common MV lamps.

Table 3.3.1. Performance Summary of Mercury Vapor Lamps

Lamp Power* *W*		**CRI**	**CCT**** *K*	**Initial Lumens**	**Life** *hr*	**Initial Efficacy at 100 hr†** *lm/W*	**Mean Efficacy at 40–50% Life‡** *lm/W*
50	Minimum	20	3200	1,050	6,000	22	13
	Median	45	4100	1,575	8,000	30	24
	Maximum	50	5700	1,900	24,000	40	33
75	Minimum	20	3200	2,700	16,000	36	24
	Median	45	4100	2,700	18,000	36	30
	Maximum	50	5700	3,000	24,00	40	32
100	Minimum	15	3200	1,100	6,000	11	8.3
	Median	40	4100	4,000	2,4000	40	26
	Maximum	60	7000	4,500	2,4000	45	37
175	Minimum	15	3700	5,100	16,000	29	21
	Median	40	4300	7,800	24,000	45	39
	Maximum	50	6800	8,900	24,000	51	43
250	Minimum	15	3200	3,200	12,000	13	11
	Median	43	4100	8,900	24,000	36	24
	Maximum	50	6700	13,700	24,000	55	45
400	Minimum	15	3700	1,500	12,000	37.5	13.25
	Median	43	4000	21,000	24,000	53	36
	Maximum	50	6500	24,000	24,000	60	49
1000	Minimum	15	3700	13,000	16,000	45	13
	Median	40	4100	45,200	24,000	58	45
	Maximum	50	6300	52,240	24,000	64	52

Table 3.3.1 (continued)

* A minimum of three different manufacturers had to produce the type and similar wattage to have that wattage class listed in this table.
** Correlated-color temperature is not a performance metric; the values are listed to show the range of available CCTs for the product.
† Initial efficacy is initial lumens divided by the lamp rated power (the power use of the ballast is not factored into this table).
‡ Mean efficacy is the mean lumen value provided by the manufacturer divided by the lamp rated power (the power use of the ballast is not factored into this table). Lumen depreciation still occurs after this point.

3.3.3 Electrical Characteristics

Because MV lamps have an additional electrode at one end of the arc tube to assist in lamp starting, they do not require a separate starter circuit. These lamps typically require an open-circuit voltage of approximately twice the operational lamp voltage to initiate and sustain the arc discharge.

Figure 3.3.3 shows the energy balance from a typical 400-W MV lamp.[11] Although this diagram dates from the mid-1970s and is for one lamp wattage, the diagram is representative of how the input power is used in this lamp type. The percentage values in parentheses are the portion of power for that input or output per rated lamp wattage. Typically, only 15 percent of the power used by the lamp is actually converted into visible radiation. The efficiency of the conversion of power into radiation increases with power. As shown in Figure 3.3.3, MV lamps produce equal or more energy in the IR region than in the visible light region.

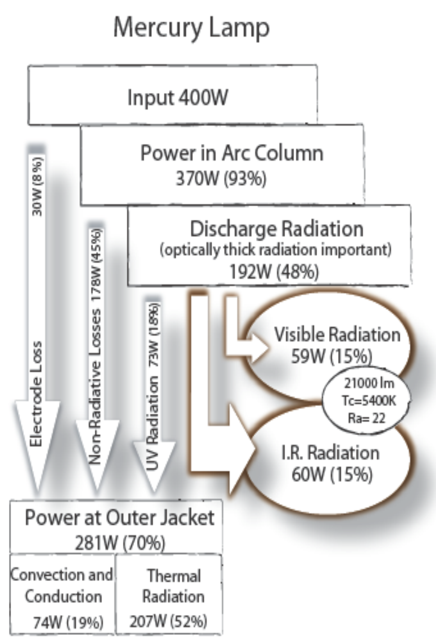


Figure 3.3.3. Sample Power Flow of a Mercury Vapor Lamp

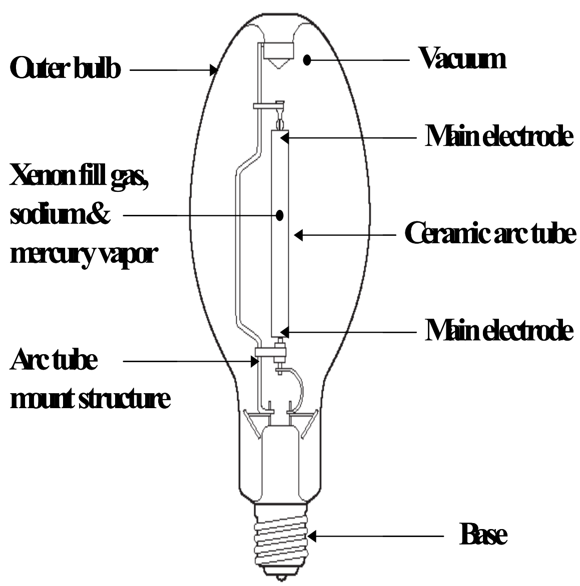
3.4 HIGH-PRESSURE SODIUM LAMPS

HPS lamps were introduced in the 1960s, before the introduction of MH lamps. HPS lamps are currently the most efficacious HID light source, ranging from 38 to 150 lm/W, with typical efficacy being greater than 80 lm/W. These values are initial lamp efficacy (rated lamp lumens/rated lamp power) and do not take in account any ballast losses. The 38 lm/W value is from a directional (reflector-type) lamp. This is an atypical lamp and its low efficacy is not representative of HPS lamps in general. Typical HPS lamps have low CCT (*e.g.*, 2100 K) and low CRI (*e.g.*, 22), but there are some enhanced-spectrum HPS lamps that have a higher CRI (and a higher CCT as a byproduct of the change in spectrum).

HPS lamps are in use in public (*e.g.*, outdoor roadway), commercial, and industrial sectors. Although HPS lamps are available in wattages from 35 to 1000; the most common wattages in these sectors range from 50 to 500. Typical applications include vehicular traffic areas (*e.g.*, roadways and parking lots) and pedestrian areas (*e.g.*, public-access areas, subways, and parks). HPS lamps are also used in commercial and industrial applications where color quality may not be critical (*e.g.*, storage and loading areas, and corridors). Many of these applications overlap with MH applications, creating competition between the technologies for market share.

3.4.1 Lamp Construction

Figure 3.4.1 shows the basic construction of HPS lamps. Similar to MV lamps, they have an inner arc tube and an outer bulb. The arc tube is made of a ceramic material that contains electrodes, a sodium and mercury amalgam, and a small amount of xenon gas. No starter probe is present in the HPS arc tube, and a high-voltage, high-frequency pulse is used to ionize the starting gas. The high temperatures needed to vaporize sodium dictate the arc tube geometry and material. Further, the highly corrosive nature of sodium, especially at elevated temperature and pressure (700 °C/27 kPa [3.9 pounds per square inch]), precludes the use of certain materials (*e.g.*, quartz). An amalgam reservoir inside the arc tube helps to stabilize pressure, similar to amalgam-based fluorescent lamps. This allows HPS lamps to operate in any physical orientation, simplifying stocking and installation.[12]



Source: GE Lighting, *High-Intensity Discharge Lamps Catalog,* 2003. Reproduced with permission.[9]

Figure 3.4.1. High-Pressure Sodium Lamp Construction

The lamp's outer glass envelopes are typically elliptical in shape and are made of a hard glass that protects the arc tube from damage. Usually, an outer envelope contains a vacuum that reduces convection and heat losses from the arc tube to maintain high efficacy.[12]

In some HPS lamps, an additional coil is wrapped around the outside of the ceramic arc tube to assist in starting the lamp.[12] This coil is similar in function to the starting probe in probe-start MH and MV lamps. This type of HPS lamp can directly replace MV lamps and operate on the same ballast without an ignitor. However, HPS retrofit lamps produce significantly more light for the same wattage. Therefore, to realize any energy savings, a lower-wattage HPS retrofit lamp should replace a higher-wattage MV lamp.

3.4.2 Lamp Performance

The high luminous efficacy of HPS lamps corresponds to the emittance of sodium in the yellow-orange portion of the visible spectrum, to which the human visual system responds most efficiently. The efficiency of HPS lamps is critically dependent on the specific vapor pressure of sodium in the arc tube. Any deviation from this optimum pressure results in reduced performance of the lamp. Notwithstanding, HPS lamps offer the highest efficacy of HID sources, achieving 64 lm/W for 35-W sources and up to 133 lm/W for 1000-W sources. HPS lamps of 100 W or more have efficacies over 100 lm/W. Rated lifetimes of 24,000 hours are typical, with some long-life lamps rated at 40,000 hours. These lamps have an expected LLD value of 10 percent at mean rated life.

A historical perspective of how these values have changed in the 40 years since HPS lamps entered the market can be found in an IESNA "significant paper." A 1965 publication in *Illuminating Engineering* stated that, with initial efficacy in excess of 100 lm/W, "10,000 hour lumen maintenance has been measured on laboratory test lamps at over 90 percent. Median life at the present time is in the 3,000- to 6,000-hour range. From an engineering viewpoint it is reasonable to expect that this can be increased as techniques for constructing the lamps are improved."[13] From the data in Table 3.4.1, it appears that the comment was true in that HPS lamp life has improved and efficacy somewhat improved. The historical perspective shows that, since the introduction of the HPS lamp to the market 40 years ago, the efficacy of the HPS lamp has increased 20 to 30 percent and HPS lamp life has significantly increased.

Table 3.4.1. Performance Summary of High-Pressure Sodium Lamps

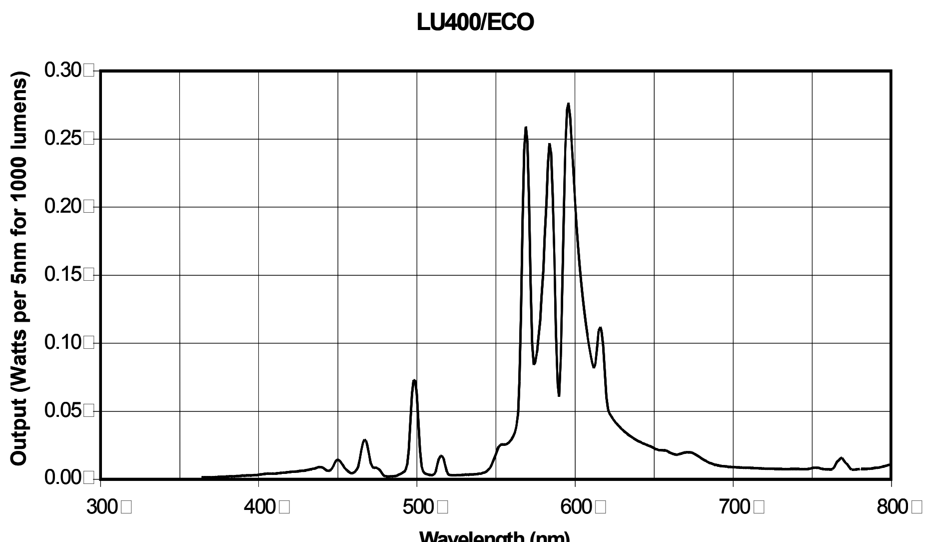
Lamp Power* *W*		**CRI**	**CCT**** *K*	**Initial Lumens**	**Life** *hr*	**Initial Efficacy at 100 hr†** *lm/W*	**Mean Efficacy at 40–50% life‡** *lm/W*
35	Minimum	21	1,900	2,100	16,000	60	55
	Median	22	1,900	2,250	16,000	64	58
	Maximum	22	2,100	2,250	24,000	64	59
50	Minimum	17	1,900	2,300	6,000	46	40
	Median	22	1,900	4,000	24,000	80	72
	Maximum	85	2,700	4,000	30,000	80	72
70	Minimum	17	1,900	3,350	6,000	48	41
	Median	22	1,900	6,300	24,000	90	76
	Maximum	83	2,500	6,500	40,000	93	84
100	Minimum	17	1,900	4,900	10,000	49	42
	Median	22	2,100	9,500	24,000	95	80
	Maximum	85	2,700	10,500	40,000	105	95

Table 3.4.1 (continued)

150	Minimum	17	1,800	5,900	6,170	39	41
	Median	22	2,100	15,000	13,500	100	90
	Maximum	85	2,500	16,000	14,400	107	96
200	Minimum	21	2,000	21,400	24,000	107	90
	Median	22	2,100	22,000	24,000	110	99
	Maximum	25	2,100	22,000	40,000	110	99
250	Minimum	15	2,000	9,500	9,000	38	32
	Median	22	2,100	27,000	24,000	112	99
	Maximum	85	2,500	29,000	40,000	121	109
400	Minimum	22	2,000	18,000	9,000	45	38
	Median	22	2,100	48,500	24,000	121	111
	Maximum	85	2,500	54,000	40,000	135	122
1000	Minimum	21	2,000	125,000	15,000	125	112
	Median	22	2,100	138,750	24,000	139	126
	Maximum	25	2,100	146,000	40,000	146	136

* A minimum of three different manufacturers had to produce the type and similar wattage to have that wattage class listed in this table.
** Correlated-color temperature is not a performance metric; the values are listed to show the range of available CCTs for the product.
† Initial efficacy is initial lumens divided by the lamp rated power (the power use of the ballast is not factored into this table).
‡ Mean efficacy is the mean lumen value provided by the manufacturer divided by the lamp rated power (the power use of the ballast is not factored into this table). Manufacturers select the time at which they provide the mean lumen data, which vary between 40 and 50 percent of rated life. Lumen depreciation still occurs after this point. Also, not all manufacturers publish mean lumen values, which can be higher than the initial efficacy values because the mean lumens were not provided. This column is based on mean lumens published by manufacturers.

Figure 3.4.2 shows the SPD for a typical HPS lamp. During warm-up, the lamp's color appearance shifts from red to blue, before stabilizing at the characteristic yellow-white.[2] A typical CCT value is 2100 K with a CRI of 22. Higher CCT values are possible at the cost of reduced efficacy and lifetime. The highest commercially available CCT is 2700 K with a CRI of 85.[14] Applying diffuse coatings does not significantly change the SPD of HPS lamps because most of the radiation emitted by the lamp is in the visible portion of the spectrum.



Source: OSRAM SYLVANIA, 2003. Reproduced with permission.[10]
* Same distribution for bare and coated lamps.

Figure 3.4.2. Spectral Power Distribution* of High-Pressure Sodium Lamps

3.4.3 Electrical Characteristics

Given their arc tube geometry and lack of starting probes, HPS lamps require an ignitor to generate the high-voltage pulse necessary to initiate the electrical arc across the electrodes. Once the ignitor initiates the arc, the cold lamp requires approximately 3 to 4 minutes of warm-up time to attain full light output, with a typical re-strike time of 1 to 3 minutes.

Figure 3.4.3 shows the energy balance from an example 400-W HPS lamp.[11] Although this diagram dates from the mid-1970s and is for one lamp wattage, the diagram is representative of how the power is used. The percentage values in parentheses are the portion of power for that input or output per rated lamp wattage. Only 30 percent of the power used by the lamp is actually converted into visible radiation. The efficiency of the conversion of power into radiation increases with power. Very little lamp power (approximately 1 percent) is emitted in the UV range. Some power (20 percent) is emitted in the IR range; however, more power is emitted in the visible range. The values in Figure 3.4.3 are consistent in relationship to the energy output of an HPS lamp as listed in Table 3.2.2.

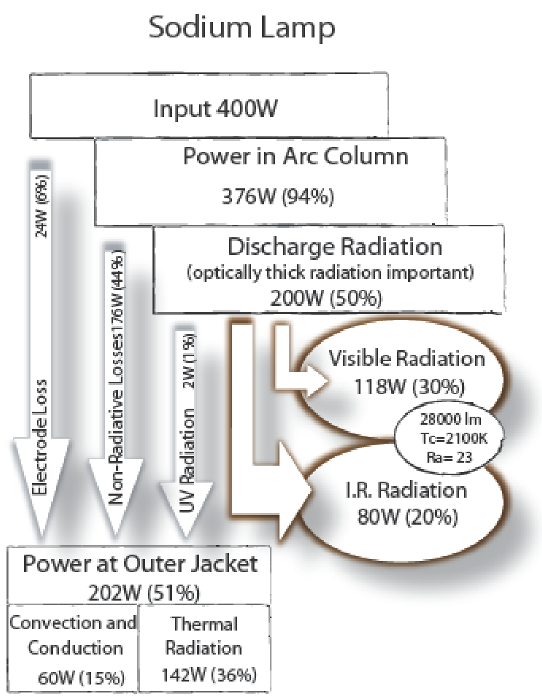
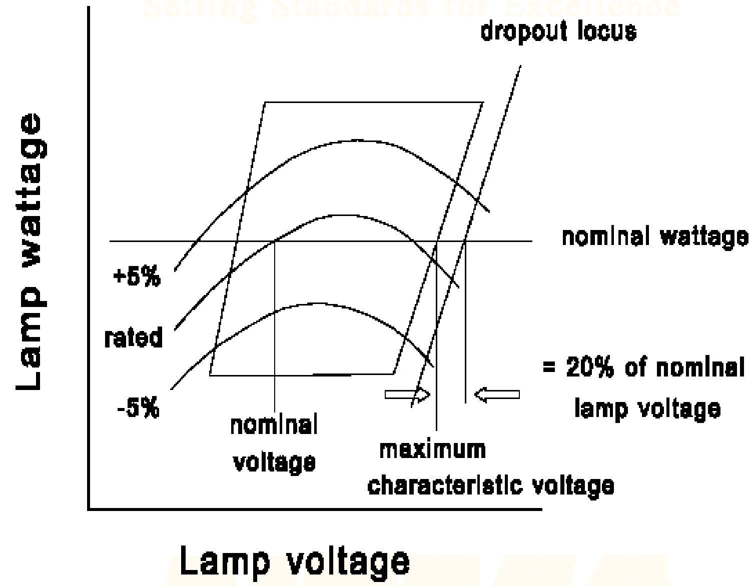


Figure 3.4.3. Sample Power Flow of a 400-Watt High-Pressure Sodium Lamp

Unlike a typical MV or MH lamp, where voltage remains relatively constant throughout its lifetime, the arc-tube voltage increases significantly during the operating life of HPS lamps. Sodium is lost over the operating lifetime of the lamp, and the arc voltage rises as the ratio of sodium to mercury changes. Although the voltage rises over life, the technology needs to operate a constant wattage. Therefore, HPS ballasts must compensate for the change in operating lamp voltage to maintain an acceptable average wattage. The lamp/ballast combination "constitutes a dynamic system in which the intrinsic voltage rise of an HPS lamp is either amplified or attenuated by the nature of the characteristic curve of the ballast on which the lamp is operated."[15] Figure 3.4.4 illustrates the boundary conditions that restrict the performance of the lamp and the ballast to certain acceptable limits. These boundary conditions, due to their shape on the graph, are referred to as the trapezoid-shaped boundaries.[16] HPS ballasts operate HPS lamps within this trapezoid for any input voltage within the designed range of the ballast.



Source: NEMA, 2001. Reprinted by permission from ANSI C78.42-2001, *High-Pressure Sodium Lamps*.[16]

Figure 3.4.4. Trapezoid Boundary for High-Pressure Sodium Ballast Design

Toward the end of the lamp's life, the lamp-operating voltage will rise to a level beyond the ballast's capability to sustain the arc. At this point, the lamp will start, warm up to full brightness, and extinguish. The repeating of this sequence is known as cycling and signals end-of-life for HPS lamps. If the lamp is then not replaced within a reasonable amount of time, premature failure of the ballast can occur. In the 1990s, the industry introduced non-cycling HPS lamps. Manufacturers increased the xenon pressure and added a starting strip on the arc tube to assist starting. They also reduced the mercury dose and included lead-free construction. This type of lamp operates on standard HPS ballasts. Non-cycling lamps, with lowered additive dose construction, do not have a voltage rise at end-of-life. Because sodium loss cannot be eliminated completely, the lamp will gradually become fully unsaturated in the useful operating regime at some point in life. As the lamp then ages, its operating point will begin to shift downward and to the left on the watts-volts plot.[17] Other research in the 1990s found that a specific combination of mercury and sodium in the lamp to maintain mercury and sodium pressures led to a lamp in which the voltage did not significantly increase over life.[18] Through the use of this specific relationship and changing the material of the emitter in the lamp, less sodium was lost and lumen maintenance was slightly improved.

3.5 METAL HALIDE LAMPS

Developed in the 1960s after HPS lamps, MH lamps offer an excellent combination of quality, performance, and flexibility for "white light" applications. The first lamps were probe-start quartz (circa 1960), followed by pulse-start quartz (circa early 1990s) and then pulse-start ceramic (circa late 1990s). The sources provide a significant amount of light for the package.

Unlike MV and HPS lamps, MH lamps have many suitable uses in both interior applications and exterior applications. The lamps are available in a wide range of CCTs (2900 to 10000 K) and CRIs (65 to 90). The small physical dimensions and high intensity of the arc make it an ideal point source around which to create application-specific light distributions through precise optical design in reflector lamps and fixtures. MH lamps are used in public, commercial, industrial, and residential sectors. The lamps are even used in transportation activities like vehicle forward lighting and range in wattages from 20 to 2000. Low-wattage (below 150) lamps are used for floodlighting and recessed lighting. Very low-wattage MH lamps (20 to 60) can be found in exterior accent and landscape luminaires (both residential and commercial) and retail track lighting. Also, since around the year 2000, very low-wattage MH lamps can be found in automotive headlights. Medium-wattage MH lamps (150 to 500) typically are used in area (*e.g.*, parking lot and pedestrian walkways), roadway, low-bay, and high-bay applications. Finally, high-wattage MH lamps are used in some parking lots, search lights, and stadium/sports lighting.

Some manufacturers produce MH retrofit lamps capable of directly replacing other lamps. Some lamps are designed to replace MV lamps of similar wattage, and operate on the same MV ballasts. However, like HPS retrofit lamps, MH retrofit lamps produce significantly more lumens for the same wattage. For example, replacing a 400-W MV lamp with a 400-W MH retrofit lamp generates about twice the light of the original MV lamp. MH lamp manufacturers have also developed self-ballasted, very low-wattage (under 40 W) PAR38 lamps intended as direct replacement for higher wattage halogen and incandescent reflector lamps. These PAR38 lamps are used in high-end retail applications and even grocery stores.

3.5.1 Construction

The standard MH lamp is similar to MV lamp technology; the lamp is essentially an MV lamp containing one or more metal halides (usually iodides) which vaporize in the lamp arc.[19] The added compounds broaden the MV spectrum, producing better color rendering and lamp efficacy in MH lamps.

The use of metal halides presents two advantages. First, metal halides are more volatile at typical lamp operating temperatures than pure metals. This allows metals with desirable emission properties to be introduced into the arc at reasonable arc tube temperatures. Second, metal halides do not readily react with a fused silica arc tube, instead remaining in the arc. When the lamp attains full operating temperature, metal halides in the arc tube partially vaporize. As halide vapors approach the high-temperature central core of the discharge, they dissociate into halogen and metals, with the metals radiating their light spectrum. As halogen and metal atoms move near the cooler arc tube wall by diffusion and convection, they recombine, and the cycle repeats.[20]

Figure 3.5.1 and Figure 3.5.2 compare and contrast power flow of two 400-W MH lamps. Although dated, the diagrams illustrate how different metal halides used in MH lamps affect SPD and overall lumen output.[11] Figure 3.5.1 is a tin iodide (SnI) lamp and produces 24,000 lumens, CCT of 4100 K, and a CRI of 91. In contrast, another lamp at the same wattage and type (MH) has very different output. Figure 3.5.2 is a dysprosium iodide (DyI) lamp and produces 32,400 lumens, CCT of 5250 K, and a CRI of 85.

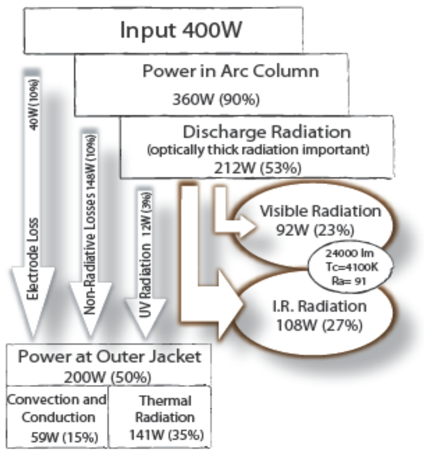


Figure 3.5.1. Tin Halide

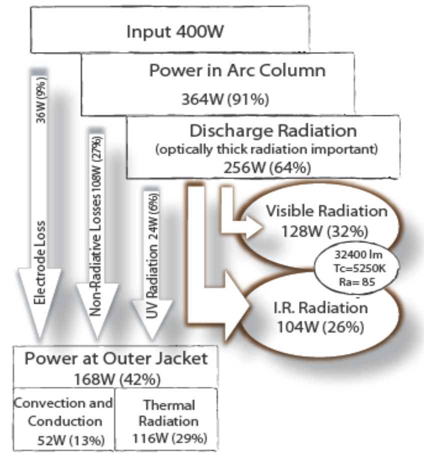


Figure 3.5.2. Dysprosium Iodide

MH lamp construction is similar to that of MV lamps. One significant difference is that arc tubes of MH lamps are usually smaller for equal wattages. The arc tube is typically made of either fused quartz or ceramic. MH arc tubes operate at a higher temperature and pressure than their MV counterparts. Quartz arc tubes typically use a white coating at their ends to increase temperature and vaporization of metal halides by trapping thermal energy inside the arc tube. Replacing quartz in the arc tube with ceramic materials enables the lamp to operate at even higher temperatures and pressures, resulting in improved efficacy, CRI, and color stability.

An elliptical outer bulb, usually made of borosilicate glass, contains the arc tube. The bulb protects and buffers the arc tube and internal electrical connections from the environment. The outer envelope contains low-pressure inert gas (*i.e.*, nitrogen) or a vacuum, which not only helps minimize the oxidation of internal components, but also provides a margin of safety against threat of arc tube rupture (also known as non-passive failure). The outer envelope also provides additional thermal buffering for a more stable arc temperature. The glass itself absorbs the majority of UV energy.[20]

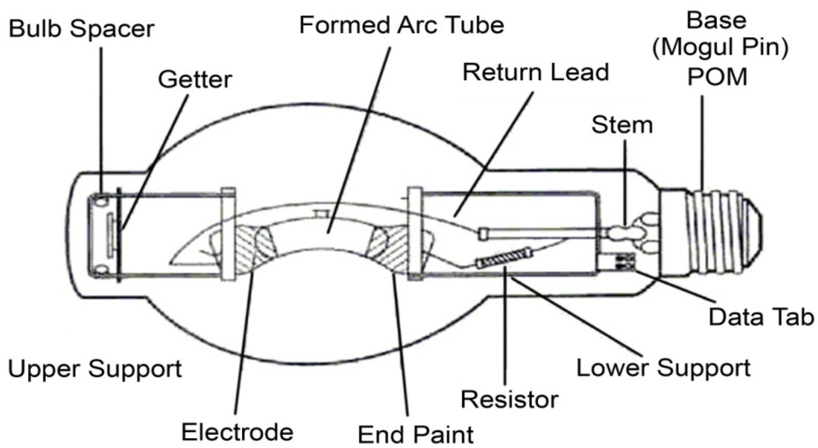
Manufacturers may coat the outer glass bulb with diffusing material. Usually, this is a phosphor coating that helps change emission spectra for small improvements in CRI. However, the primary purpose of the coating is to reduce source brightness of the lamp for glare control. The technology advantage of MH lamps is their capability to emit the desired spectra without the addition of a phosphor coating. Adding a diffuse coating to the lamp reduces the efficiency and effectiveness of luminaires with optics.

The outer bulb contains wires suitable for high temperatures to conduct electricity to the arc tube and structural components to support the arc tube. There might be other components, including resistors, diodes, and bimetallic switches used to help start the arc discharge, as well as devices called “getters” to purify the atmosphere in the outer lamp. Most MH lamps use getters to control (reduce or eliminate) impurities that, if present in the outer jacket of MH lamps in sufficient concentrations, can compromise performance.

Like other lamps in the HID group, MH lamps typically have screw bases (medium or mogul) made from brass, nickel, or special alloys to minimize corrosion. A characteristic of MH arc tubes is that they can take different forms and can be made from different materials.

In a horizontally operated MH lamp, the arc discharge bows away from the axis of the arc tube due to convection currents. The MH pool (liquid) moves to the center of the arc tube. The bowed arc moves farther from the metal halides than when the lamp is vertical, causing the metal halides to cool. This lowers the vapor pressure of MH chemicals and decreases the concentration of metals in the arc, resulting in loss of light. The bowed arc moves closer to the top of the arc tube wall, causing its temperature to increase. The higher heat loading on the arc-tube material can result in a decrease in life of approximately 25 percent. Therefore, manufacturers use additional shapes to compensate for this sensitivity in operating position. High-output lamps designed to operate horizontally use a special base and socket, such as the ANSI EP39 Mog position-oriented mogul base, to help ensure proper arc tube orientation and position.

Figure 3.5.3 shows a bowed arc-tube shape that follows the natural bowing of the horizontal arc.[20]

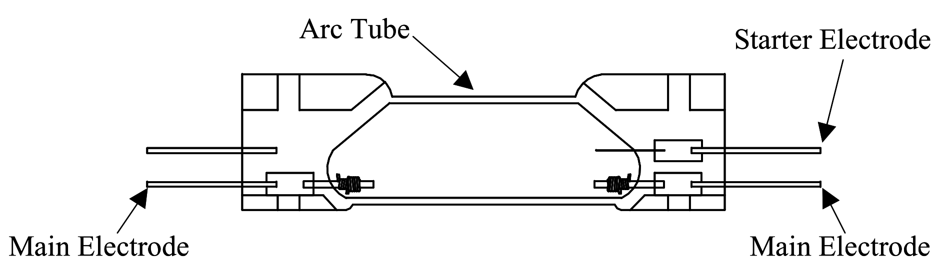


Note: POM means position oriented mogul.

Source: OSRAM SYLVANIA, *High Intensity Discharge Metalarc® Lamps*, 1998.[20] Reproduced with permission.[10]

Figure 3.5.3. Formed Arc-Tube Configuration for Horizontal Metal Halide Lamps

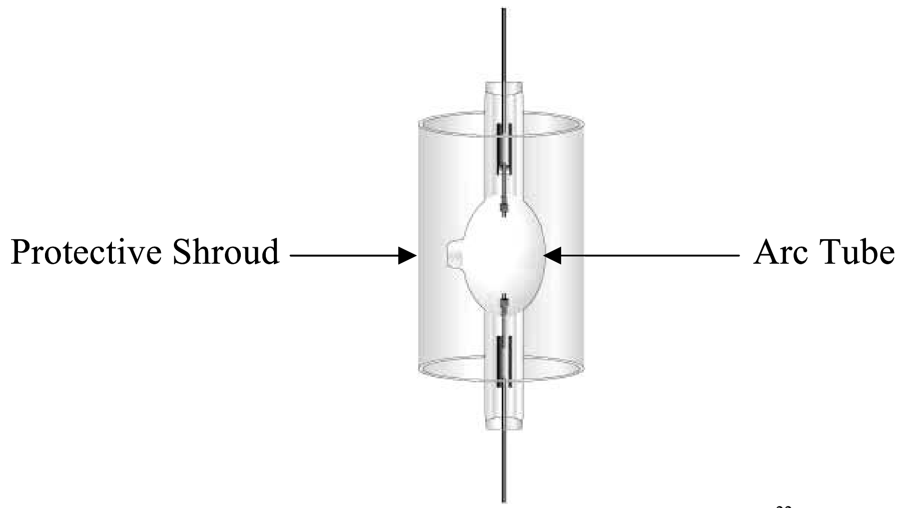
Figure 3.5.4 shows an asymmetric arc tube with offset electrodes. In this design, the electrodes are lower in the arc tube body, and the arc discharge bows to the center of the arc tube.



Source: Philips, 2003. Reproduced with permission.[21]

Figure 3.5.4. Offset Electrode Configuration for Horizontal Metal Halide Lamps

Some lamps use a transparent sleeve, called a shield or shroud, to surround the arc tube (Figure 3.5.5). The sleeves are useful as heat shields because they help the arc tube achieve a uniform temperature profile. Shrouds also prevent the outer jacket of the lamp from breaking in case of a violent arc-tube failure; however, shrouds are not the only method of protection (*e.g.*, some new ceramic tubes have a wrapped wire instead of a sleeve). HID lamps with protective shrouds carry the ANSI O-rating, signifying that the lamps meet ANSI requirements for safe operation in an open-luminaire not equipped to protect against violent failure. To prevent user misapplication, the industry developed unique socket and base combinations in both medium bases and mogul bases for these open-luminaire lamps.



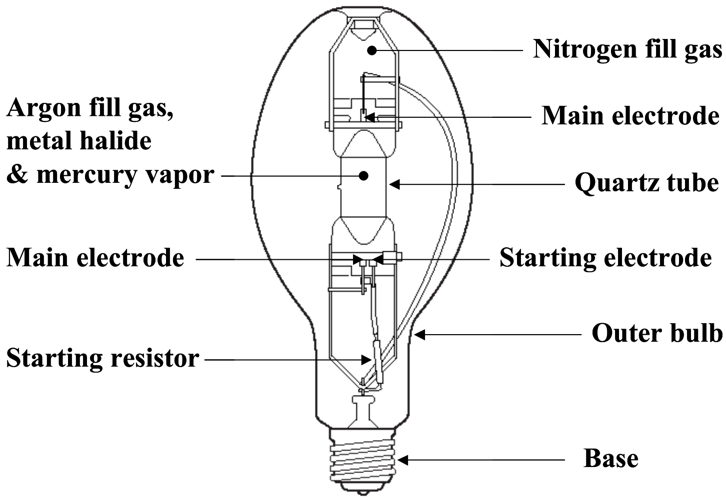
Source: Venture Lighting, 2003. Reproduced with permission.[22]

Figure 3.5.5. Metal Halide Arc Tube with a Shroud

Some applications, such as sports lighting, use MH lamps without outer jackets. Due to high levels of UV energy in their emission spectra, luminaires that operate with these lamps (no outer jackets) require a glass cover to absorb some of this harmful UV radiation.

3.5.1.1 Probe-Start Quartz Metal Halide Lamps

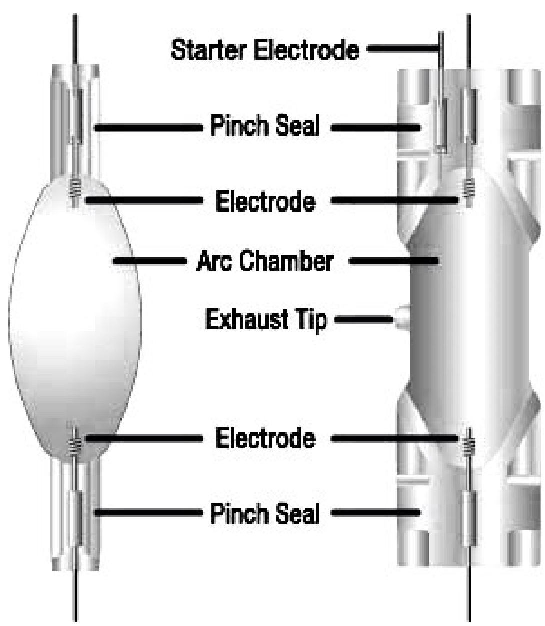
The first MH lamp was the probe-start lamp (Figure 3.5.6), where the arc tube is shaped into what is called the classic pinched body. These lamps require a starter electrode (or probe) in the arc tube. The lamp body must also contain a system that provides for cutting starting voltage after the lamp is started, typically with a bimetal switch. Continued application of high starting voltages can severely shorten lamp life. The location and type of bimetal switch can restrict the lamp operating position, as the bimetal must achieve a certain temperature to function.



Source: GE Lighting, *High-Intensity Discharge Lamps Catalog,* 2003. Reproduced with permission.[9]

Figure 3.5.6. Metal Halide Lamp Construction

An evolutionary development of the probe-start lamp configuration is the formed-body arc tube. Manufacturers can mold arc tubes into unique shapes such as an ovoid (Figure 3.5.7), significantly improving performance. The contour of the formed-body arc-tube wall follows the shape of the arc, thereby allowing for a more uniform temperature profile for the arc tube. Also, formed-body arc tubes have much smaller pinch-seal areas. This allows MH chemicals to heat up more rapidly than those in conventional pinched-body arc tubes, resulting in a shorter warm-up time than pinched-body arc tubes of the same wattage. Probe-start MH lamps typically use pinch-seal designs (Figure 3.5.7) that have a starter electrode (or probe) to help initiate the breakdown of arc-tube gases.



(a) Ovoid (b) Pinched-Body

Source: Advanced Lighting Technologies Inc., 2003. Reproduced with permission.[22]

Figure 3.5.7. Common Arc Tubes

3.5.1.2 Pulse-Start Quartz Metal Halide Lamps

Thirty years after probe-start MH lamps entered the market, pulse-start MH (PMH) lamps were introduced. Pulse-start MH lamps are similar to probe-start; however, PMH lamps lack a starting probe in the arc tube.

Pulse-start MH lamps were the first to incorporate formed-body arc tubes, but this arc-tube shape is not exclusive to pulse-start configurations. Some manufacturers still use pinched-body arc tubes in their PMH lamps.[23]

Pulse-start MH lamps have a higher starting-gas fill pressure to decrease the starting time and minimize the transport of electrode material to the wall. These improvements extend life (up to 50 percent longer) and improve lumen maintenance (up to 33 percent) compared with traditional probe-start MH lamps.

3.5.1.3 Pulse-Start Ceramic Metal Halide Lamps

The most recent development in MH arc tube design incorporates the ceramic arc tube. Like formed-body arc tubes, this pulse-start technology lacks a starter probe. This arc tube represents the newest evolution in the development of MH lamps. The lamp performance and electrical-characteristic segments of this MH lamp chapter discuss the improvements in performance from these new shapes and materials.

3.5.2 Lamp Performance

Commercially available MH lamps have initial efficacies from 30 to 125 lm/W (excluding ballast losses). The lowest efficacy is related to a type of directional lamp and is not typical of the MH lamp family. Depending the on the type of MH lamp, the CRI ranges from 65 to 90, far superior to virtually every other HID lamp (MV and HPS). This unique capability results from manufacturers' ability to tailor the spectral outputs of the lamps.

Metal halides are binary compounds consisting of halogen and metal elements. Halogens are a group of non-metals including fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At). Iodine in the form of ions (also known as iodide) is the most common halogen used in MH lamps. Bromine is the other halogen used, but less often than iodine. Metal halides are additive compounds, so nearly any metal can be combined with halogens. However, certain metals are not used because of toxicity, instability, or other problems with the metals at the required vapor pressures. Excluding those metals, roughly 50 different metals can still be used in MH lamps. Using two metals at a time, the number of possible combinations (not counting variations in concentration) is 1,225. The metals can be used three, four, or five at a time, giving 19,600, 230,300, or 2,118,760 combinations.[24] Although many possible combinations exist, metals are typically selected with strong emission lines in the desired portion of the spectrum.

Typical metals used in MH lamps include indium (In), tin (Sn), and the rare earth (RE) elements which include scandium (Sc), yttrium (Y), and 15 lanthanoids: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadodinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

Other metals that have been explored are alkaline earth halides, a series of metals that comprise Group 2 of the periodic table: beryllium (Be), magnesium (Mg), calcium (Ca), strontium (Sr), barium (Ba), and radium (Ra). A 1976 study examining improving MH lamps found that:

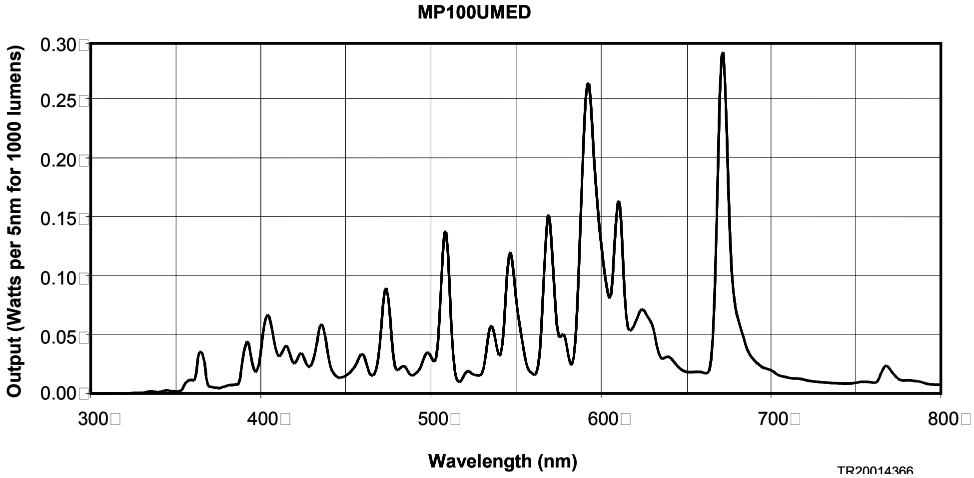
> In many cases, *e.g.*, sodium and the rare earth halides, an increase in vapour pressure will result in a higher luminous efficacy. In other cases, *e.g.*, the alkaline earth halides, one could enhance the emission at certain wavelengths and thus substantially improve the colour rendering properties of the lamp.[25]

Metal halides in these lamps have characteristic emissions that are spectrally selective. Some metals emit visible radiation in narrow spectral bands, generating specific colors to the eye (*i.e.*, Na for yellow-orange, Tm for green, and In for blue). A 1985 study examining the spectral properties of MH lamps with rare earth iodides found that the spectra of the metal can be selectively used:

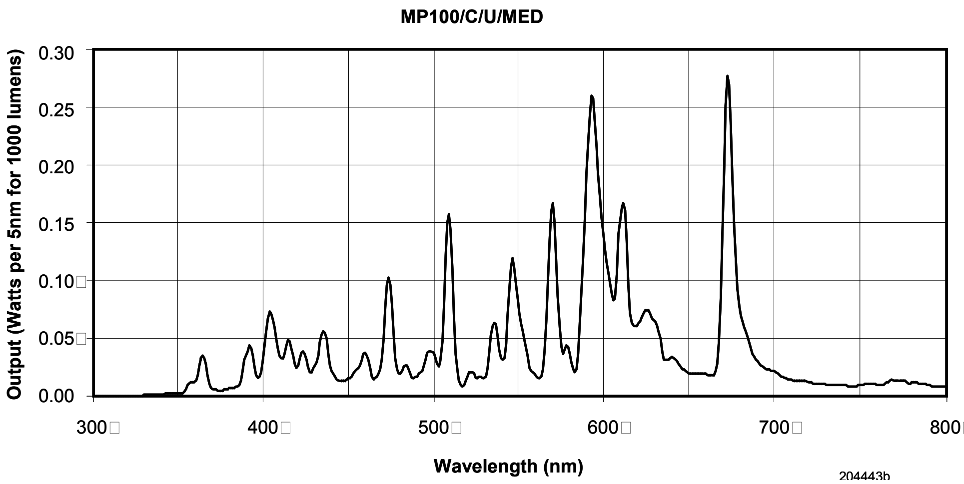
> This results in the possibility of optimizing the spectra for distinct applications. In 400 W, lamps the highest efficacies obtained were reached with Ce-Na and Pr-Na mixtures, η = 110 to 115 lm/W [LPW]. The best colour rendering properties can be obtained with Tm and Dy (Ra>80).[26]

Other metals such as tin, when introduced as halides, radiate predominantly as molecules, providing continuous band spectra across the visible spectrum. Various combinations of these halides can create a wide range of CCT and CRI for these lamps.

Phosphor coatings also change the spectral emission of these lamps. Because phosphors convert shorter-wavelength radiation to longer-wavelength radiation, these phosphors effectively lower the CCT of lamps by approximately 300 K. Although a slight improvement in CRI may occur, the primary function of a phosphor coating of MH lamps is to create a more diffuse light source. These combinations of metals and their halides as well as phosphors (to a lesser extent) create an almost infinite palette of possibilities, giving MH lamps flexibility in light-output design unique to the HID sources. Figure 3.5.8 shows typical SPD plots for MH lamps with and without a phosphor coating.



(a)



(b)

Source: OSRAM Sylvania, 2003. Reproduced with permission.[10]

Figure 3.5.8. Spectral Power Distribution of Metal Halide Lamps (a) Without Phosphors and (b) With Phosphors

Because the physical operating orientation of the lamp affects performance, MH lamps are typically life-rated and lumen-rated in the vertical operating position. For example, MH lamps classified as universal orientation (able to operate in any orientation) achieve their rated performance in the vertical position.

3.5.2.1 Probe-Start Quartz Metal Halide Lamps

When operated to specifications, probe-start lamps have a rated life from 10,000 to 20,000 hours with an average efficacy of 84 lm/W. The actual efficacy varies by both the lamp wattage and the lamp type (omni-directional lamps are more efficacious than directional lamps). The rated LLD is about 25 percent at 40 percent of rated life.

Color quality is an important aspect of MH lamps. The average CRI for probe-start lamps is 76; actual values range as in Table 3.5.1). However, CRI only examines a sample of eight (R1-R8) pastel color samples, atypical for some applications. Therefore, in addition to the CRI values, many MH lamp manufacturers are now reporting the R9 (deep red color) for specification in interior applications, especially retail. The R9 value of probe-start lamps is negative.[27] Therefore, probe-start lamps have limited use in interior applications and are not practical for retail installations. Over life, the color shift among the same batch of MH lamps can be from 300 to 800 K.[28]

Table 3.5.1. Performance Summary of Probe-Start Metal Halide Lamps

Lamp Power* *W*		**CRI**	**CCT**** *K*	**Initial Lumens**	**Life** *hr*	**Initial Efficacy at 100 hr†** *lm/W*	**Mean Efficacy at 40% Life‡** *lm/W*
50	Minimum	70	2900	3,200	10,000	64	30
	Median	85	3500	3,525	10,000	71	46
	Maximum	92	4000	4,100	20,000	82	55
70	Minimum	70	2900	2,610	3,200	37	43
	Median	92	4000	5,000	9,000	71	55
	Maximum	96	6500	6,200	20,000	89	66
100	Minimum	65	2900	6,000	9,000	60	48
	Median	92	4000	8,400	15,000	80	59
	Maximum	96	6500	9,500	20,000	95	71
150	Minimum	65	2800	5,400	2,800	36	48
	Median	95	3850	11,950	10,000	80	60
	Maximum	96	6500	14,000	20,000	93	70
175	Minimum	55	3000	10,000	7,500	57	43
	Median	65	4000	13,600	10,000	78	50
	Maximum	75	10000	15,000	10,000	86	69
250	Minimum	62	3000	17,500	7,500	70	38
	Median	65	4000	20,750	10,000	83	55
	Maximum	90	10000	23,000	20,000	92	78
360	Minimum	60	3600	31,700	15,000	88	57
	Median	65	4000	36,000	20,000	100	65
	Maximum	80	4300	43,200	30,000	120	98
400	Minimum	60	3000	25,000	8,000	63	44
	Median	65	4000	36,050	20,000	90	60
	Maximum	90	10000	43,000	20,000	108	84
1000	Minimum	65	3200	72,000	6,000	80	52
	Median	65	3700	110,000	12,000	110	86
	Maximum	72	5500	120,000	18,000	120	96
1500	Minimum	60	3400	125,000	3,000	83	67
	Median	65	4000	163,000	3,000	109	93
	Maximum	92	5500	170,000	6,000	113	102

* A minimum of three different manufacturers had to produce the type and similar wattage to have that wattage class listed in this table.
** Correlated-color temperature is not a performance metric; the values are listed to show the range of available CCTs for the product.
† Initial efficacy is initial lumens divided by the lamp rated power (the power use of the ballast is not factored into this table).
‡ Mean efficacy is the mean lumen value provided by the manufacturer divided by the lamp rated power (the power use of the ballast is not factored into this table). Manufacturers select the time at which they provide the mean lumen data, which vary between 40 and 50 percent of rated life. Lumen depreciation still occurs after this point. Also, not all manufacturers publish mean lumen values. The mean efficacy values can be higher than the initial efficacy values because the mean lumens were not provided, and this column is based on mean lumens.

3.5.2.2 Pulse-Start Quartz Metal Halide Lamps

When operated to specifications, the rated life of pulse-start MH lamps is 15,000 to 30,000 hours with efficacies in excess of 100 lm/W. The LLD is about 25 percent at 40 percent of rated life. Table 3.5.2 summarizes the performance of PMH sources.

Table 3.5.2. Performance Summary of Quartz Pulse-Start Metal Halide Lamps

Lamp Power* *W*		**CRI**	**CCT**** *K*	**Initial Lumens**	**Life** *hr*	**Initial Efficacy at 100 hr†** *lm/W*	**Mean Efficacy at 40 % Life‡** *lm/W*
50	Minimum	60	2900	2,900	10,000	58	30
	Median	70	3300	3,300	10,000	66	41
	Maximum	92	4000	4,100	20,000	82	55
70	Minimum	65	2800	2,610	3,200	64	40
	Median	82	3500	5,200	12,000	74	54
	Maximum	96	6500	7,400	20,000	106	79
100	Minimum	65	2700	5,800	7,500	58	48
	Median	73	3200	8,500	15,000	85	58
	Maximum	92	4200	9,500	20,000	95	72
150	Minimum	60	2800	5,400	2,800	73	55
	Median	85	3550	12,500	12,000	83	64
	Maximum	96	6500	15,000	20,000	100	75
175	Minimum	62	3200	13,000	10,000	74	57
	Median	65	4000	16,000	15,000	93	71
	Maximum	75	4200	17,500	15,000	100	80
250	Minimum	60	3000	16,500	10,000	66	52
	Median	70	4000	22,500	15,000	90	69
	Maximum	94	6500	26,000	20,000	104	80
320	Minimum	62	3200	22,500	10,000	70	28
	Median	70	4000	30,000	20,000	94	72
	Maximum	90	5000	34,000	20,000	106	84
350	Minimum	62	3200	25,000	10,000	88	57
	Median	67	4000	34,500	20,000	99	74
	Maximum	90	5000	51,628	30,000	120	98
400	Minimum	60	3600	27,000	10,000	68	39
	Median	65	4000	39,850	20,000	100	75
	Maximum	90	6500	44,000	20,000	110	90
1000	Minimum	65	3400	80,000	5,000	80	64
	Median	65	3900	110,000	12,000	110	88
	Maximum	92	5500	120,000	15,000	120	96

* A minimum of three different manufacturers had to produce the type and similar wattage to have that wattage class listed in this table.

** Correlated-color temperature is not a performance metric; the values are listed to show the range of available CCTs for the product.

† Initial efficacy is initial lumens divided by the lamp rated power (the power use of the ballast is not factored into this table).

‡ Mean efficacy is the mean lumen value provided by the manufacturer divided by the lamp rated power (the power use of the ballast is not factored into this table). Manufacturers select the time at which they provide the mean lumen data, which vary between 40 and 50 percent of rated life. Lumen depreciation still occurs after this point. Also, not all manufacturers publish mean lumen values. The mean efficacy values can be higher than the initial efficacy values because the mean lumens were not provided, and this column is based on mean lumens.

3.5.2.3 Pulse-Start Ceramic Metal Halide Lamps

Advancements in arc tube materials led to the development of the ceramic arc tube. This material allows MH lamps to operate at even higher temperatures and vapor pressures. The technology is currently available only in wattages up to 400. Improvements in ceramic arc-tube design will soon make higher-power versions available. When operated to specifications, ceramic metal halide (CMH) lamps have a rated life of 6,000 to 20,000 hours with an efficacy of approximately 88 lm/W. The LLD improves over quartz MH lamps to about 20 percent at 40 percent of rated life. CMH lamps also have excellent CRI with an average CRI of 88. Typical R9 values are positive but very low.

Recent advances in CMH lamp design allow for high CRI (90), good R9 (over 40), greater efficacy, and improved lumen maintenance. These new CMH lamps, currently produced by Philips, are medium wattage (315 and 210) and have an efficacy over 120 lm/W. In contrast, other similar wattage CMH or PMH lamps are between 90 and 115 lm/W. The lumen output of these new lamps is 90 percent at 40 percent of rated life; in contrast to typical 80 percent for CMH, 75 percent for PMH, and 70 percent for MH. The developers of this new CMH lamp attribute the performance enhancements to operating the lamp on an electronic ballast; using new chemical additives (presumably different metal halides); and optimized arc tube shape.[27]

Table 3.5.3 summarizes the performance of CMH lamps.

Table 3.5.3. Performance Summary of Pulse-Start Ceramic Metal Halide Lamps

Lamp Power* *W*		CRI	CCT** *K*	Initial Lumens	Life *hr*	Initial Efficacy at 100 hr† *lm/W*	Mean Efficacy at 40–50% Life‡ *lm/W*
50	Minimum	81	2900	1,400	6,000	72	49
	Median	85	3000	2,225	10,000	76	52
	Maximum	92	4200	3,500	15,000	82	57
70	Minimum	80	2900	2,850	9,000	51	37
	Median	88	3000	5,800	12,000	81	61
	Maximum	95	4300	7,300	24,000	104	93
100	Minimum	81	3000	5,700	10,000	57	40
	Median	85	3000	8,200	12,500	82	62
	Maximum	93	4100	9,500	24,000	95	72
150	Minimum	80	2800	9,100	5,000	61	55
	Median	90	3000	12,800	10,000	85	63
	Maximum	96	5500	15,500	24,000	103	83
250	Minimum	85	3000	20,750	12,000	83	66
	Median	90	4050	22,500	20,000	90	73
	Maximum	94	4200	25,000	24,000	115	103
400	Minimum	85	3000	34,800	15,000	87	70
	Median	90	4000	38,000	20,000	95	78
	Maximum	90	4200	41,000	20,000	102	82

* A minimum of three different manufacturers had to produce the type and similar wattage to have that wattage class listed in this table.
** Correlated-color temperature is not a performance metric; the values are listed to show the range of available CCTs for the product.
† Initial efficacy is initial lumens divided by the lamp rated power (the power use of the ballast is not factored into this table).
‡ Mean efficacy is the mean lumen value provided by the manufacturer divided by the lamp rated power (the power use of the ballast is not factored into this table). Manufacturers select the time at which they provide the mean lumen data, which vary between 40 and 50 percent of rated life. Lumen depreciation still occurs after this point. Also, not all manufacturers publish mean lumen values. The mean efficacy values can be higher than the initial efficacy values because the mean lumens were not provided, and this column is based on mean lumens.

3.5.3 Electrical Characteristics

The additional electrode located at one end of the arc tube in probe-start MH lamps allows operation without an ignitor circuit, making it possible for MH lamps to share the same ballast with MV lamps, within limits. However, MH ballasts typically have more rigorous operating requirements than MV ballasts. Thus, MV lamps can operate universally on similar wattage probe-start MH ballasts, but the opposite is true only with specially designed MH lamps. Lamp manufacturers took advantage of this and produced MH lamps that could operate on MV lamp ballasts. However, replacement raises issues of economy and utility, in addition to technological issues. The engineering analysis (chapter 4) of this document addresses these issues.

Pulse-start MH lamps lack the secondary electrode found in probe-start MH lamps, resulting in different electrical requirements and performance. Using an ignitor, a high-voltage pulse (typically in excess of 3 kilovolts) is applied directly across the main electrodes to initiate the arc, resulting in faster starting and re-strike times than for probe-start MH lamps. The warm-up and re-strike times are 2 minutes and 3 to 4 minutes, respectively. That is an improvement over the typical probe-start MH warm-up time of 4 minutes and a re-strike time of 15 to 20 minutes; these results are also better than those of typical MV and HPS lamps.

3.6 HAZARDOUS MATERIALS

Mercury is a double-sided issue in the lighting industry. Although HID lamps are more efficacious than halogen/incandescent (mercury free) lamps, mercury is needed in most vapor discharge sources (both low and high pressure). However, use of these sources displaces more mercury released in energy production, so it still is beneficial to use a discharge source over incandescent/halogen. Amount of mercury in an HID source varies by lamp type and wattage.

Table 3.6.1 is from a 2008 report about trends in mercury use in products.[29] In both 2001 and 2004, lamps represented about 8 percent of the total use of mercury in products. Overall mercury usage in lamps decreased by roughly 6 percent between 2001 and 2004. The total use of mercury in HID lamps increased by 15 percent, whereas use by fluorescent lamps decreased by 14 percent between 2001 and 2004. The reason total mercury usage was relatively flat, while these two lamp types changed significantly, is that fluorescent lamps have been designed to use less mercury and more HID lamps were specified between the 2 years. Table 3.6.2 breaks down the mercury sold by HID lamp type. The vast majority of mercury usage in HID lamps is in the MH family.

Table 3.6.1. Total Mercury Sold in Lamps

All Lamps	Total Mercury Weight *lb (kg)*	
	2001	**2004**
Fluorescent	16,657 (7,555.48)	14,372 (6,519)
High Intensity Discharge	2,749 (1,246.93)	3,156 (1,431.54)
Compact Fluorescent	877 (397.80)	1,479 (670.86)
Neon	1,103 (500.31)	1,070 (485.34)
Short Arc	10 (4.54)	17 (7.71)
Miscellaneous	42 (19.05)	24 (10.89)
Total	21,438 (9,724.11)	20,118 (9,125.37)

Table 3.6.2. Total Mercury Sold by High-Intensity Discharge Lamp Type

Lamp Type	2001 Total Mercury Sold by Weight *lb (kg)*	Portion of total HID *%*	2004 Total Mercury Sold by Weight *lb (kg)*	Portion of total HID *%*
MH	2,145 (972.95)	78	2,426 (1100.42)	77
Ceramic MH	N/A	0	31 (14.06)	1
HPS	401 (181.89)	15	453 (205.47)	14
MV	203 (92.08)	7	213 (96.62)	7
Total	2,749	--	3,156	--

Mercury is integral to the three lamp types, though more for some than others. HPS lamps have been designed with low mercury and even no mercury content (labeled as such in catalogs). The typical amount of mercury for HPS lamps from 35 to 1000 W is between 10 and 50 milligrams (mg). By definition, MV lamps must contain mercury. The typical mercury content in MV lamps from 50 to 1000 W is between 50 and 150 mg. Because MH technology is related to MV lamps, mercury plays a vital role in these lamps. The typical mercury content in MH lamps from 39 to 50 W is between 1 to 10 mg; 70 to 250 W is between 5 to 50 mg; 350 to 400 W is between 30 to 100 mg; and 400 to 2000 W is between 100 to 150 mg.

In response to reducing mercury in products, mercury-free HID lamps have been investigated. A 2007 research paper considered replacing mercury with noble gases. Noble gases include helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn). The study experimented with Ne, Ar, and Xe. “The presented results emphasize Ar and Xe as proper Hg substitute candidates.”[30]

Lead is sometimes present in HID lamps as solder for the coupling. A toxicity characteristics leaching procedure test on HID lamps classifies them as hazardous waste for mercury and lead. Therefore, they are subject to the Universal Waste Rule published by the U.S. Environmental Protection Agency (EPA) on July 6, 1999.[31] State and local regulations will vary on their disposal, but recycling is recommended.

A small percentage of MH lamps contain the radioactive isotope krypton 85. The MH lamps that contain this radioactive isotope are primarily used in special applications of theatrical and film luminaires.

3.7 HIGH-INTENSITY DISCHARGE LAMP BALLASTS

High-intensity discharge lamp ballasts apply sufficient voltage for lamp ignition, regulate the operating current, and essentially relight the lamp at each one-half cycle of the voltage. A 1983 paper focusing on the relationship between HPS lamp voltage rise and the ballast summarized the relationship: “A lamp and ballast cannot be considered separate elements but each contributes to a dynamic system influencing each other in achieving total system performance.”[15] Although this quote was in relation to HPS lamps, it is applicable to HID lamps in general. For HPS and PMH lamps, an additional ignitor circuit generates the high-voltage starting pulse necessary to initiate the arc discharge. Typical input voltages for HID lighting systems are 120, 208, 240, 277, and 480 volts.

There are two types of HID ballasts: magnetic and electronic. The majority of ballasts sold for HID lamps are magnetic, also known as core-and-coil. The ballasts operate at 60 hertz (Hz). Within the magnetic HID ballast family, there are seven sub-types of ballasts: (1) high-reactance autotransformer; (2) reactor-normal power factor; (3) reactor-high power factor; (4) regulated-lag, also known as magnetically regulated; (5) constant-wattage autotransformer (CWA); (6) constant-wattage isolated (CWI); and (7) super constant-wattage autotransformer (SCWA). CWA has become the most popular HID ballast for lamp power levels above 150 W.[32] Ballast efficiency varies with rated lamp power, less ballast losses occur as the rated power increases.[b]

The other major type of ballast is electronic; currently, electronic ballasts only exist for pulse-start lamps. Within the electronic HID ballast category, there are only two types: low frequency (less than or equal to 400 Hz) and high frequency (equal to or above 100 kilohertz [kHz]). Most electronic HID ballasts are for MH lamps, with a small portion for HPS lamps, and no electronic ballasts for MV lamps. A 1990 paper comparing some of the first electronic HID ballast with conventional ballasts found that when electronic ballasts for high-pressure lamps will be different than for electronic ballasts for low-pressure discharge lamps. For electronic ballasts, “more sophisticated, forms of generators for lamp operation must be used than in the field of low-pressure discharge lamps.”[33] Unlike electronic ballasts for FL lamps, HID electronic ballasts do not always make the lamp-ballast system more efficient. In 2006, the Lighting Research Center (LRC) compared 70-W MH lamps from various manufacturers operating on both magnetic and electronic ballasts by different manufacturers. The LRC study found that ballast efficiency was directly affected by the type of ballast: “Because of design and manufacturing practicalities, the ballast efficiency of magnetic ballasts is approximately 10 percent lower than that of electronic ballasts.”[34] There are some system (lamp plus ballast) efficiency gains from converting from magnetic to electronic HID ballasts, but there are other electrical issues associated with electronic HID ballasts that affect HID lamps. During the public meeting for the framework document for the MH lamp fixture energy conservation standard, the disadvantages and advantages of electronic HID ballasts were discussed. A comment from the meeting sums up the issue of electronic HID ballasts: “Some electronic ballasts do improve lamp maintenance and lamp life, others do not; as a matter of fact, some electronic ballasts can decrease lamp life.”[35]

Long-rated operating lifetimes are one of the desirable features of HID lamps, compared with other sources. Electronic ballasts can both start and operate a lamp more “gently” than a magnetic ballast, with positive benefits in the lamp performance. A study from the mid-1990s found electronic ballasts can extend lamp life once other electrical issues are addressed: “[W]ith attention paid to the proper features of the electronic ballast, namely high extinguishing resistance, it can be concluded that lamp service life with electronic ballasts will be 1.5 to 2.0 times longer than with conventional ballasts.”[36]

One of the principal disadvantages of electronic ballasts is that the lamps operate at high frequency and this creates acoustic resonance. The LRC study comparing 70-W lamps operating on electronic ballasts describes the negative issue of acoustic resonance: “At frequencies above 4 kHz, standing pressure sound waves (acoustic resonances) build inside the lamp’s arc tube, which can lead to visible distortions and instability of the electrical discharge, light flickering,

[b] Ballast efficiency – the ratio of lamp rated power/ballast input power (P_{out}/P_{in}).

and possible cracking of the tube."[34] As stated earlier, lamp life can be extended via the use of an electronic ballast but can also be cut short if special precautions in either the ballast or lamp design are not used.

Ballast design is not the purview of this document. Therefore, only aspects of the lamp that directly affect acoustic resonance are reviewed here, specifically, arc tube size and geometry. Pressure waves are created in the lamp when the resonant frequency is close to the operating frequency. These pressure waves move through the lamp, distorting the arc tube path, which causes flicker and, in extreme cases, arc contact with the tube wall. If the arc touches the tube wall, the arc tube can crack. A cracked arc tube seriously affects the lamp and can lead to non-passive failure (*i.e.*, rupture) of the arc tube and bulb wall.

Lamp Current Crest Factor (LCCF)[c] is an aspect of either magnetic or electronic ballasts that can affect both the HID lamp life and lumen maintenance. Many within the lighting industry consider lamp life and lumen deprecation the primary performance metrics of a lamp-ballast system.[32] The lamp electrodes can be damaged by high LCCFs, which directly affects lumen maintenance and lamp life. LCCF values can range from 1.0 to infinity; however, ANSI specifies maximum LCCF values. For example, ANSI C78.43-2007 covers single-ended MH lamps from 39 to 1650 W and sets a maximum LCCF of 1.8 for 39- to 1650-W MH lamps.[37] A 2008 paper comparing the effects on lamp life and lumen depreciation for two different types of ballasts for 400-W MH lamps articulated the value of an LCCF limit: "The rationale for placing an upper limit upon the LCCF is to prevent the lamp current from falling to an unsuitably low value for a significant period of time on a half-cycle basis."[32] Lower LCCF values are better for the lamp electrode and thus are better for the lamp life and lumen maintenance. The LRC study articulated the waveform and LCCF issues of magnetic and electronic ballasts in their comparison: "An ideal sinusoidal waveform (and therefore, a magnetic ballast) cannot have an LCCF below 1.4. Most magnetic ballasts have LCCFs ranging from 1.5 to 1.7. The square current waveform of an electronic ballast allows the LCCF to approach 1.0."[34]

[c] Lamp Current Crest Factor (LCCF) – the ratio of the peak lamp current to the root-mean-square value of the lamp current.

REFERENCES

1. National Electrical Manufacturers Association. *Standards and Publications*. 2009. (Last accessed February 2, 2010.) <http://www.nema.org/stds>

2. Illuminating Engineering Society of North America. *The IESNA Lighting Handbook: Reference and Application*. M. S. Rea, Editor. 9th ed. 2002. New York, NY.

3. General Electric. *GE Lamps & Ballasts 2010 Products Catalog*. (Last accessed February 2, 2010.) <http://www.gecatalogs.com>

4. OSRAM SYLVANIA. *Lamp and Ballast Catalog*. 2008. (Last accessed February 2, 2010.) <http://assets.sylvania.com/assets/documents/Complete-Catalog.b176dbb1-d6e0-40f0-ab92-e768e58f5dc1.pdf>

5. Philips Lighting Company. *Lamp Specification and Application Guide: High Intensity Discharge Lighting*. 2008. SAG100 2008-2009. (Last accessed February 2, 2010.) <http://www.lighting.philips.com/us_en/browseliterature/download/SAG-100_2009_HID.pdf>

6. USHIO America, Inc. *General Lighting Product Catalog*. 2006. (Last accessed February 2, 2010.) <http://www.ushio.com/products/catalog.htm#GE>

7. Venture Lighting. *North American HID Lighting Specification and Energy Saving Products Guide*. 2008. Summer Edition. (Last accessed February 2, 2010.) <http://www.venturelighting.com/On-LineCatalog/VentureLightingSummer08.pdf>

8. Nelson, G. J., R. G. Gibson, and A. D. Jackson. An Efficacy Analysis of HID Lamps. *Journal of the Illuminating Engineering Society*. Winter 2001. 30(1): pp. 68–75.

9. Howley, J. G. *Personal communication*. GE Lighting. E-mail permission to use graphic to DOE via C. Updyke, NEMA. May 2, 2003.

10. Bleasby, P. *Personal communication*. OSRAM SYLVANIA. E-mail permission to use graphic to DOE via C. Updyke, NEMA. May 1, 2003.

11. Jack, A. G. and M. Koedam. Energy Balances for Some High Pressure Gas Discharge Lamps. *Journal of the Illuminating Engineering Society*. July 1974. 3(4): pp. 323–329.

12. OSRAM SYLVANIA. *Lumalux/Unalux High Pressure Sodium Lamps*. 1998. Engineering Bulletin HID009. (Last accessed February 2, 2010.) <http://ecom.mysylvania.com/miniapps/FileNet2/EngineeringBulletins/ENGR_BLTN2.pdf>

13. Louden, W. C. and K. Schmidt. High-Pressure Sodium Discharge Arc Lamps. *Illuminating Engineering*. 1965. 60(12): pp. 696–702.

14. Philips Lighting Company. *High Intensity Discharge Lighting*. Online publication SAG-100 2006. (Last accessed February 2, 2010.) <http://www.nam.lighting.philips.com/us/ecatalog/catalogs/2006_SAG100_HID.pdf>

15. Ward, P. C. Estimation of HPS Lamp Voltage Rise as a Function of Ballast Characteristic Curve Parameters. *Journal of the Illumination Engineering Society*. October 1983: pp. 157–161.

16. American National Standards Institute (ANSI). *High-Pressure Sodium Lamps*. ANSI document C78.42-2001.

17. Ingalls, P., R. Dolan, J. Plumb, H. Zhu, and E. Wyner. A Noncycling High Pressure Sodium Lamp. *Journal of the Illuminating Engineering Society*. Summer 1995. 24(2): pp. 19–25.

18. Plumb, J., G. Duggan, D. Goodman, R. Snellgrove, and E. Wyner. Emitter for Unsaturated-Vapor High Pressure Sodium Lamps. *Journal of the Illuminating Engineering Society*. Summer 1995. 24(2): pp. 26–32.

19. Work, D. E. Chemistry of Metal Halide Lamps: A Review. *Lighting Research and Technology*. 1981. 13(3): pp. 143–152.

20. OSRAM SYLVANIA. *High Intensity Discharge Metalarc® Lamps*. 1998. Engineering Bulletin HID-010-0995. (February 2, 2010.) <http://ecom.mysylvania.com/miniapps/FileNet2/EngineeringBulletins/ENGR_BLTN1.pdf>

21. Work, D., C. Mannino, B. Ives, and M. Hewitt. *Personal communication*. Philips Lighting Company, Somerset, NJ. E-mail to E. Hong, Navigant Consulting, Inc. Final illustration and permission to use provided by e-mail from M. Hewitt of Philips to Navigant via C. Updyke, NEMA. August 4, 2003.

22. Wypasek, D. *Personal communication*. Advanced Lighting Technologies, Inc. Permission to use graphic provided by e-mail to DOE via Craig Updyke of NEMA. May 16, 2003.

23. National Lighting Product Information Program. *Lighting Answers: Mid-Wattage Metal Halide Lamps* 7(1). Troy, NY: Lighting Research Center.

24. Waymouth, J.F. *Electric Discharge Lamps*. 1971. Cambridge, MA: The MIT Press.

25. Lorenz, R. Improvement of Metal Halide Lamps by Complex Formation. *Lighting Research & Technology*. 1976. 8(3): pp. 136–140.

26. Tielemans, P., P. Drop, and R. Lorenz. Spectral Properties of Metal Halide Lamps with Rare Earth-Iodide or Sc-Iodide and Sodium Iodide. *Lighting Research & Technology*. 1985. 17(2): pp. 79–83.

27. Tu, J., J. van der Eyden, T. De Baerdemaeker, J. Woods, K. Graham, A. Dunaevsky, and N. Caruso. New Advancements in Medium Wattage Ceramic Metal Halide Lamp. *Leukos*. January 2009. 5(3): pp. 152–165.

28. Deng L., C. O'Rourke, J. Fullam, and R. Hosseinzadeh. Performance of Medium Wattage Pulse Start Metal Halide Lamps. In *IESNA Annual Conference Proceedings*, Technical Papers. 2004. New York, NY. Illuminating Engineering Society of North America. pp. 193–202.

29. Northeast Waste Management Officials' Association (NEWMOA)/IMERC. Trends in Mercury Use in Products: Summary of the Interstate Mercury Education & Reduction Clearinghouse (IMERC) Mercury-Added Products Database. June 2008.

30. Franke, S., H. Schoepp, O. Langenscheidt, R. Methling, H. Hess, H. Schneidenbach. Study of Noble Gases as Mercury Substitutes in High-Pressure Discharge Lamps. *Leukos*. January 2007. 3(3): pp. 217–227.

31. U.S. Environmental Protection Agency. Hazardous Waste Management System; Modification of the Hazardous Waste Program; Hazardous Waste Lamps; Final Rule. Federal Register. July 6, 1999. Vol. 64, no. 128, pp. 36466–36490.

32. Flory IV, I. L. and S. Rahman. Metal-Halide Lamp Life and Lumen Depreciation: A Comparison of Two, 400 Watt Discharge Lamp Ballasting Systems. *Leukos*. January 2008. 4(3): pp. 173–185.

33. Rasch, E. and E. Statnic. Behavior of Metal Halide with Conventional and Electronic Ballasts. *Journal of the Illuminating Engineering Society*. Summer 1991. 20(3): pp. 88–96.

34. National Lighting Product Information Program (NLPIP). *Low-wattage Metal Halide Lighting Systems*. Specifier Reports. October 2006. 10(1). (Last accessed February 2, 2010.) <http://www.lrc.rpi.edu/nlpip/publicationDetails.asp?id=911&type=1>

35. U.S. Department of Energy–Office of Energy Efficiency and Renewable Energy. Comments from the Public Meeting for Energy Conservation Program: Energy Conservation Standards for Metal Halide Lamp Fixtures: Public Meeting and Availability of the Framework Document. Transcript for Docket EERE-2009-BT-STD-0018 Regulatory Identification Number (RIN) 1904-AC00.

36. Fukumori, F., H. Nishimura, K. Uchihashi, and M. Fukuhara. A Study of HID Lamp Life when Operated by Electronic Ballasts. *Journal of the Illuminating Engineering Society*. Winter 1995. 24(1): pp. 41–47.

37. American National Standards Institute (ANSI). *American National Standard for Electric Lamps—Single-Ended Metal Halide Lamps*. ANSI document C78.43-2007.